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Science and War.[1]

AUSTIN H. CLARK, U. S. National Museum.

In times of national emergency it is incumbent upon all of us, both as individuals and as members of any organization to which we may belong, to do everything within our power for the public good. We who are engaged in science are no longer justified in appraising the world and our fellow men in the light of their bearing upon our specialty, as in times of peace we are inclined to do. We must broaden our outlook and integrate our activities and our thoughts with that will-to-victory that animates us all.

Victory, as we all know, will be achieved primarily by our armed forces working in cooperation with those of our allies, and in collaboration with our diplomats. An all-out victory, however, demands that we give thought to certain social and economic aspects of present-day and future existence that lie beyond the scope of military and diplomatic activities.

Most of these social and economic aspects are already being cared for by various agencies either directly under, or more or less closely connected with, Governmental agencies. There are, however, a few of outstanding importance, though involving a relatively small number of individuals, that can better be carried on, or at least supervised or encouraged, by organizations such as the Washington Academy of Sciences or similar bodies than by any Governmental agencies.

Academies of science are representative of the scientific activities in the communities in which they are situated. The Washington Academy of Sciences includes within its membership representatives of all the branches of science in the Government service and in the local educational institutions. Each member has his special affiliations, but the Academy as a whole is capable of independent action insofar as such action does not interfere with the work, or run counter to the policies, of the various agencies with which its members are affiliated.

As a preface to the discussion of the needs of science in the present emergency may I, at the risk of being boresomely repetitious, tax your patience for a few minutes by reviewing briefly the history of science in relation to human society?

From the earliest times of which we have a record to the present day, the history of man has been marked by constant changes in the social systems, changes that often were abrupt and violent. One form of social structure or of government has succeeded another. Small but powerful social or political units have grown by accretion or by conquest into great kingdoms or empires. These kingdoms or empires eventually have decayed or fallen apart, the fragments maintaining a longer or shorter separate existence, or becoming merged into other larger units.

Together with these frequent social, political, or economic readjustments of the past we see a constant and fairly continuous development of other forces which to a large extent are independent of transient political conditions. We note a growing interest in and understanding of the products of the earth and their uses. We also are able to trace the ever-increasing subjugation of the forces of nature, which

[1] Address of the retiring president of the Washington Academy of Sciences delivered at the 309th meeting of the Academy, January 15, 1942. Received January 15, 1942.

more and more come to be the servants instead of the enemies of man.

The greatest of all human achievements was the control and use of fire. We have no knowledge of when or how fire was first transformed from a terrifying natural phenomenon into man's most useful servant, for no human race exists that does not know, to some extent at least, the use of fire. Second among human achievements was the fashioning and use of tools and weapons. The origin of the use of tools is lost in the far distant past. The earliest tools we know were crudely fashioned from stone. The technique of making tools gradually improved, and many of the stone axes, choppers, projectile points, and other objects fashioned by early human types are marvels of technical skill. Then came the weaving of textiles from plant or animal fibers and the molding of pottery vessels, followed by the appearance of bronze. Not long after the appearance of bronze utensils of various sorts, the wheel and axle appeared in Asia, soon spreading to Europe.

From the Bronze Age onward the knowledge of the use of natural products and the control of natural forces have shown a fairly continuous development, and to an ever-increasing extent have become an integral part of the fundamental basis of progressive human societies.

Since the beginning of the present century the advance in the knowledge and understanding of the products and forces of nature has been greater than in all the thousands of years preceding—or at least since the subjugation of fire, the first fashioning of tools, and the domestication of animals and plants.

Whether we like the idea or not, we are now living in an age, and under conditions, in which science plays a dominant part, and the established scientific principles that underlie many of the most familiar of our present-day improvements were unheard of, or considered fallacious, no longer than a generation ago. Our children regard as commonplace necessities all sorts of things that to us of the older generation still seem to be more or less miraculous innovations—the talkies, the radio, the airplane, the wire-photograph, the neon light, the modern motor-car, and many others. This is self-evident to all; but the implications inseparable from a culture based ever more intensively and extensively on increasingly abstruse science are not as yet fully appreciated.

The progress that through the ages has been made in the understanding of natural phenomena and in the utilization of natural products is continuing at an accelerated pace, and will continue in the future, in spite of what may happen in the next few years. It may be locally obstructed, or even brought to an end, but somehow, somewhere, it will carry on.

The present struggle is no more a contest in the military field than it is in the field of science. It is quite possible to win the war on the battle front, but lose it in the laboratory. The Germans and the Japanese both are well aware of this. So are our friends the Russians. They are waging their battles in their laboratories as vigorously as on the firing line.

We in this country must see to it that, so far as possible, the steady advance of science is maintained. At the present time we are utilizing to the maximum extent our scientific resources and our scientific personnel to aid in our war effort. We are doing this, I have reason to believe, more extensively, more efficiently, and more effectively than any other country.

But this is not enough. Various branches of science not of immediate military application are in the long run quite as essential for our progress and our welfare as are those forms of engineering, of physics, and of chemistry that underlie the construction and the use of modern implements of warfare. These are the many and varied types of pure science, lines of work leading to results seemingly of no importance that all too often are regarded merely as a form of mental exercise undertaken solely for the personal satisfaction and gratification of the person concerned. What we call pure science is simply a branch of science for which no economic application has as yet been found. But at any time a body of uncoordinated facts may suddenly and unexpectedly

fit into an integrated whole, to our great advantage. Without its advance fringe of competent workers in pure science constantly probing the great unknown and accumulating masses of data with no apparent immediate application, the broader aspects of scientific progress soon would languish, and we would eventually lose heavily. Pure science is likely to suffer severely in times like the present—in times when it would seem to be the wisest course to give it the maximum encouragement.

Recently I have received, passed by the German censor and wrapped in several unfolded signatures of an edition of Horace, an elaborate memoir on the Isopoda, a group of wretched little crustaceans commonly called wood-lice or sow-bugs. The last publication received by the National Museum Library from the Institute of Scientific Research, Manchukuo, was devoted to a detailed account of the butterflies of Yablonya, Pin-chiang Province. Evidently the Germans and the Japanese consider it worth while to encourage work in lines of pure science apparently quite unconnected with military affairs. If it is worth while for them—and we must admit that both nations are military-minded—why is it not worth while for us?

In Germany and in Japan things are done in ways that are not practicable with us. If Der Führer considers the detailed study of wood-lice worth while from the point of view of furthering the Nazi aims, wood-lice will be studied, and the people will accept as of value to themselves, even if they do not applaud, the results of the studies. In Japan, science has been brought to high popular favor in the past 40 years through the example and excellent leadership of a group of powerful and highly respected noblemen, and a number of these noblemen, including some members of the Imperial Family and the grandson of the last Shogun, are enthusiastic entomologists.

There is a natural tendency to say, "Well, if the Germans and the Japanese choose to squander their slender resources by supporting and publishing trivialities of this sort, let them go ahead and do it." But let us look at the matter from a different viewpoint. In the future, if any American student wishes to study the Isopoda of the Philippines and the Netherlands East Indies, he must base his work on the memoir referred to, and in the same way students of the butterflies of eastern Asia must follow the Japanese lead. No scientific man objects to working with his colleagues in any country. To that extent science is international. What patriotic scientific men do object to is the possibility of having in the future to play second fiddle to scientific men in other lands, not because they are in any way inferior, but because they were unable to carry on their work.

In this country we do not have a Führer who can dictate what science may or may not do, and we do not want one. Neither do we have a group of powerful noblemen to chart a course for us. We do not want them either. At the same time, we have no desire to be outdone by countries dominated by these human phenomena.

In this country, progress in any line of science is mainly dependent upon the willingness of the people to support work in that particular line which, in turn, is dependent upon popular interest and appreciation.

We have among us at the present time very many people who are by no means science-minded. Their attitude varies all the way from passive superciliousness to outspoken hostility. Not a few go so far as to say that science is the cause of the present war, such people being the spiritual descendents of those who, a little over a hundred years ago, tried to suppress the friction match on the ground that it would stimulate the activity of fire-bugs. Many in our country districts have their own peculiar ideas about the moon and stars, ideas in regard to which they are exceedingly sensitive, while in the cities many are very supercilious regarding the value of entomology except, perhaps, when it comes to discouraging the activities of bed bugs.

We who are engaged in scientific work, and who understand its importance in the general complex of present-day human affairs, often fail to realize how recently science has been able more or less success-

fully to overcome various forms of popular prejudice and to secure the favor of a very large section of the general public.

The present popular attitude toward science can not properly be understood without some knowledge of the public attitude in the more or less recent past. I propose therefore to digress for a moment in order to indicate briefly the changes that have taken place here and in England since the early days of the settlement of the country. At that time, in the reign of Queen Elizabeth, Galileo was still a student at the University of Pisa, Tycho Brahe had just completed his observatory, and Paracelsus and Agricola only recently had died. In those days science was almost wholly included in the subject of theology, and scientific work was restricted within narrow bounds by the dogmas of the theologians. In the words of the Marquess of Salisbury science was "the knowledge gained not by external observation, but by mere reflection. The student's microscope was turned inward upon the recesses of his own brain; and when the supply of facts and realities failed, as it very speedily did, the scientific imagination was not wanting to furnish to successive generations an interminable series of conflicting speculations."

For some time there had been a growing restiveness against the restrictions placed on scientific investigations by the theologians. This restiveness began to take the form of concerted action in the first half of the seventeenth century. As early as the reign of Charles I, about 1645, there existed in England an organization referred to by the Hon. Robert Boyle, seventh son of the first Earl of Cork, as the "Invisible College." This "Invisible College" was first suggested by Theodor Haak (or Hank), a German from the Palatinate, then resident in London. It consisted of weekly meetings at which the results of experimental work in philosophy, in its broad sense, were discussed. This was rather an unorthodox procedure for the time, but those who attended the meetings were among the ablest men of England, and included theologians as well as others. One of the theologians was Dr. John Wilkins, afterward Bishop of Chester, who had married Robena, sister of Oliver Cromwell. Another participant was Sir Christopher Wren, who later laid down the plan for the College of William and Mary.

According to Dr. Cromwell Mortimer, "had not the Civil Wars happily ended as they did, Mr. *Boyle* and Dr. *Wilkins*, with several other learned men, would have left *England*, and, out of esteem for the most excellent and valuable Governor, *John Winthrop* the younger, would have retir'd to his new-born Colony [Connecticut] and there have established that *Society for promoting Natural Knowledge*, which those Gentlemen had formed, as it were, in *Embryo* among themselves."

Emigration to America was, however, forestalled. On November 28, 1660, the "Invisible College" became visible as "The Royal Society of London for Improving Natural Knowledge." On the Wednesday following, word was brought that King Charles II approved the design of the meetings; in October, 1661, the King offered to be entered one of the Society; and in the next year the Society was incorporated under the name of the Royal Society, the first charter of incorporation passing the Great Seal on July 15, 1662.

Although the Royal Society remained in England, both the College of William and Mary and Harvard College received considerable amounts of money from the estate of the Hon. Mr. Boyle after his death in January 1691–92.

Science now began to assume a new aspect. Charles II had in effect declared that there is nothing irreligious in reporting facts. So records of observed facts and their interpretation in the light of other facts began to supersede introspection in which the aid of facts was regarded as superfluous, combined with interminable commentaries on the works of Aristotle.

Following the Restoration, science in England became largely an occupation of the aristocratic and the wealthy and for the most part was followed along lines that had little or no economic application. In the public mind it came to be identified more or less completely with the aristocracy

and to be regarded as partaking of the same aloofness from the general run of human affairs that characterized the social life of the upper classes. The natural result of this was that when, in the Victorian era, the champions of the lower classes began to gain a considerable following, they, or at least many of them, attacked science as one of the perquisites of the aristocracy. This attitude is well illustrated by Charles Dickens's "Mudfog Papers" published on the occasion of the first meeting of the British Association for the Advancement of Science.

Since that time science in England gradually has come more and more into popular favor. Applied science has made rapid strides and is now quite as fully developed and as highly regarded as it is in any other land. The rise in the prestige of applied science, however, has not been accompanied by any noticeable decline in the popularity of pure science, so that here we find the two types advancing side by side in more or less ideal balance. But, unfortunately, science in England still does not have the complete confidence of the public, and is not by any means free from neglect, disparagement, or even attack in the popular press.

In this country the history of science has been somewhat different. In early colonial times scientific effort was devoted mainly to making known the natural resources of the new land, particularly the plant and animal life. But applied science early attracted the attention of the colonists. In 1612 John Rolfe perfected a method of curing tobacco so that it would reach England in good condition, and as early as 1617 Samuel Argall wrote that "ground wore out with maize will bring English grain."

In later colonial times applied science, especially in certain engineering branches, was systematically discouraged in the fear that the colonies might become competitors of the mother country in the production of manufactured goods.

It was possibly partly as a reaction from this suppression that after the Revolution science stood high in the favor of the representatives of the American people, its most insistent and powerful advocates being Thomas Jefferson of Virginia, Benjamin Franklin of Pennsylvania, and John Adams of Massachusetts. But it was some time before the new country was sufficiently well organized to enable the people to devote much thought to science. When they did, a spontaneous interest, taking various strange and crude forms, appeared, particularly in the agricultural areas. This crude popular science—and pseudoscience—gradually became amalgamated with the more orthodox science of the schools and colleges, and we note, especially after the middle of the last century, an enormous expansion of applied science in all forms, later very largely supported by Federal and State appropriations made possible by active and widespread interest among all the different groups in our population.

In this country popular interest in science is twofold, arising both from the vista of economic betterment resulting from applied science, and from its appeal to the imagination. We all like to look forward to the day when we shall be even more comfortable than we are now. But we all have a nonmaterial side. We like to get away from the hard realities of every-day life and to contemplate the unknown, and beyond that the unknowable. We all would like to know more about the world we live in. What would we find a few hundred miles down in the earth, or 20,000 feet below the surface of the sea? We would like to know more about the stars; are there any other worlds like ours? And what is it like in interstellar space? We would like to know more about ultimate human origins—indeed, about very many things concerning which our present information is vague and fragmentary. Now although popular interest in science is more general and more widespread in this country than it is in any other, it tends to gravitate in these two directions, toward the directly economic and toward the mysterious. Between these two extremes lies a broad intermediate field in which our people as a whole take little interest, but which is intensively cultivated elsewhere. This is the descriptive branch of pure science, the results of which are of no immediate eco-

nomic import and are not mysterious.

Popular interest in science must not only be maintained, it must be increased if we are to hold our own in the years to come, for whether carried on under Government support or in endowed institutions of learning, the full development of our scientific potentialities is dependent upon a sympathetic public attitude. In order to secure, to maintain, and to increase public interest in and sympathy toward scientific work, and to convert the still disconcertingly numerous unbelievers, it is essential that we continually provide the public with news regarding scientific progress in all lines of interest to them, from both the material and non-material or philosophical viewpoints. Such impersonal news is especially desirable in times of national emergency, when it can be made to serve as a welcome relief from distressing accounts of mortal combat.

Fortunately in this respect we are in an excellent position. More and better science is carried in our daily press and other journals than in those of any other country, and science is less frequently disparaged and denounced here than elsewhere. There is still room for improvement, but nevertheless conditions are reasonably satisfactory. For this we have chiefly to thank the National Association of Science Writers the members of which, in addition to knowing science, know the public mind and are able to present the advances in science in terms everyone can understand. We are fortunate in having among the members of the Academy two of the outstanding members of this Association, Mr. Thomas R. Henry of the *Evening Star* (a past president) and Dr. Frank Thone of *Science Service*.

Publicity for science is not of direct concern to the Academy, but I wish to bring to your attention the vital importance of this aspect of scientific activity—for salesmanship is as important for science as it is for everything else—and to urge you all to do everything you can to help in this essential work.

Progress in science is possible only with the support of an interested and appreciative public. It is also possible only through the efforts of a carefully selected and adequately trained personnel. This is a matter that heretofore scarcely has received the attention it deserves.

At the present time a very serious danger to our continued progress in science has arisen. This is the induction into the Army of many young men who would be of vastly greater value to the country if they were permitted to continue their studies, or to remain in research positions. The matter is further complicated by the fact that as a rule the most valuable of these young men are those most likely to enlist on their own initiative.

After the last war there was a marked scarcity of able young scientific men. This was most noticeable, perhaps, in the biological sciences, though it was more or less noticeable in other branches as well. Many promising young men were killed. Others, as a result of several years spent in the various armies, found themselves unable to make the necessary readjustment to scientific work. Still others tried to readjust themselves but were only partially successful. Breaking the thread of continuity of effort between the impressionable boy in the formative period and the mature man can not but result in a certain amount of dislocation. We are reminded of the old Berber proverb—

> Teaching boys is like ploughing earth,
> Teaching men is like ploughing rock,
> Teaching old men is like ploughing water.

There are two ways out of this dilemma. Either the student may be placed on a deferred list so that he may be enabled to continue his studies uninterruptedly, or he may be assisted in carrying on his work, to whatever degree may be found practicable, while in the service.

Many young botanists and zoologists would welcome an opportunity for collecting specimens and continuing their studies in regions new and strange to them. Such material as they collected could be sent home to be identified, or to be stored until their arrival. Activities of this nature carried on in their spare hours would go far toward overcoming that feeling of bore-

dom that afflicts almost everyone stationed at an isolated army post or naval base, and there is no reason to believe that these activities would in any way detract from their military efficiency.

It is not assumed that anything of this sort would be practicable with an army in the field, on ships at sea, or at certain naval bases. But there are numerous places where the men of our armed forces will be stationed with nothing but monotonous routine to occupy their minds and where such recreation would be both practicable and welcome.

Not only would this work benefit the men engaged in it; it would also go far toward filling many gaps in our knowledge of the distribution of animals and plants, and of other features connected with them, and I am sure that the curators of most of our larger museums and herbaria would be glad to cooperate and to encourage most cheerfully the young men concerned. By such sympathetic assistance and encouragement the morale of many young men could be maintained, and the gap in the continuity of their work in their chosen field largely filled in.

In army posts and naval bases a young zoologist or botanist who spends his spare time catching insects or pressing plants will at first be an object of ridicule to his associates, both officers and men. His situation, however, is by no means without precedent—and most honorable precedent. It may comfort him to realize that the world's leading authority on the Hesperidae, a peculiarly difficult group of butterflies especially characteristic of America, is Brigadier General William H. Evans of the Royal Engineers, while in the Royal Navy Rear Admiral Hubert Lynes is the leading authority on a very puzzling group of small African birds. Some time ago the collections of the British Museum were enriched by a fine collection of butterflies presented by Captain Lord Byron.

There are many military men, now as well as in the past, who have, or have had, biology as a hobby and have made notable contributions to the subject. In our own Army I may mention Colonel Thomas L. Casey, Colonel Wirt Robinson, Colonel Martin L. Crimmins, and Lieutenant Colonel Edgar A. Mearns, and there are many others. Looking at the matter in a more frivolous light, is a young man using his spare time to continue his studies, and at the same time to advance our knowledge of animals and plants, any more ridiculous than an ancient tough old sea-dog in the forecastle engaged in fine embroidery work with delicately colored silks, to the accompaniment of blood-curdling oaths?

A vast amount of such work has been done by the personnel of foreign armies and navies in the past, particularly by officers in the British services. In fact, at one time our own Navy assigned interested young officers to the Smithsonian Institution for instruction in the collection and preservation of material. One of these young officers especially, Lieutenant William E. Safford, subsequently made notable contributions to the collections of the Institution. I see no reason why, in the interest of the maintenance of morale and of scientific progress, this procedure can not be revived and extended to the enlisted personnel.

Whether in its material or in its nonmaterial aspects, progress in science is dependent upon the fostering of the scientific spirit. The scientific spirit is more than mere curiosity. It is an insatiable curiosity that impels one to learn everything that is known about a given subject, and then to go further and broaden and extend that knowledge by personal investigation and research, in spite of all difficulties and discouragements—and these are always many.

The spirit of science is inborn, though it may appear in anybody, anywhere, in any class, or group, or race. We are fortunate in having a population in which the scientific spirit is widespread, though we have not always encouraged it as perhaps we should have done. We have encouraged it mainly in our graduate schools, and in them chiefly when it was directed toward some objective of more or less immediate economic interest.

In order to develop the scientific spirit to the maximum, as it must be developed if we are to hold our place in the world of the future, we must watch for it at its in-

ception, and whenever and wherever it is found encourage it. In the British Navy the average age of an officer at the time of entering the service is 12½ years. By the time a young man has attained the grade of ensign his whole outlook on life has been aligned with the Navy tradition. Something comparable to this is needed in science. Naturally, many of the boys and girls who are enthusiastic about science in their school days later devote themselves to other lines of activity. But the time and energy spent in encouraging these will be more than repaid by the superior excellence of those who finally take up science as their life work. Besides, those who, interested in science in early youth, later enter some other field of activity will form the nucleus of a sympathetic background for those who make of science their career.

Here we find a real opportunity for service on the part of the Academy. Some means should be devised whereby all the children in the local schools showing a special aptitude for science may be watched and their progress followed. If they show exceptional promise they should be encouraged and, if necessary, assisted in completing their education in the most advanced of our graduate schools. Already some of the State academies of science are performing this service to their communities through junior academies of science, or through various science clubs, or through both combined. Why should the Washington Academy of Sciences not undertake it?

We are facing a long war, and a very serious war, a war that, to a far greater extent than any previous war, will be fought on two fronts, in the field of arms and in the laboratory. Our enemies understand this thoroughly and are acting accordingly. We are building a military machine of surpassing power and efficiency. We must at the same time build up a scientific personnel of corresponding power, efficiency, and morale, reinforced by a continuous and adequate flow of highly trained and thoroughly competent replacements able to carry on successfully after the military phase of the struggle is ended. I ask you all, and each of you individually, to do all in your power toward making our scientific front invincible.

PHYSICS.—*A review of the methods for the absolute determination of the ohm.*[1]

HARVEY L. CURTIS, National Bureau of Standards.

It is nearly half a century since the critical review of Dorn[2] on the absolute determinations of the ohm was published. In that review, the methods then available were discussed and the results which had been obtained were analyzed. Since then the number of available methods has considerably increased, principally by the introduction of those that employ alternating currents. Some of the older methods, however, are still very important, so that a complete review has been undertaken of all the determinations that have been made.

The resistance of a conductor is, by Ohm's law, the ratio of the potential difference at its terminals to the continuous current through it. If both the potential difference and current are measured in terms of length, mass, time, and the permeability of a medium, the value of the resistance is in absolute units. However, most methods for the absolute determination of resistance avoid the direct measurement of either the potential difference or the current, since only the ratio of these quantities is required. In many methods there is an induced electromotive force that can be computed from the electromagnetic equations, and the current can be determined from its mechanical effects. In such cases the equations for determining the electromotive force and current can often be so combined that the resistance of a circuit, or of a portion of one, can be obtained without measuring either a current or potential difference.

The various methods that have been used are classified in Chart I. Following each

[1] Received October 11, 1941.

[2] *On the apparent value of the ohm.* Wiss. Abh. PTR **2**: 257. 1895.

specific method there is given in the chart the name of the man who proposed it. In addition to the chart a brief description is given of each method listed therein. Also there is usually given for each method an estimate of the accuracy that can be obtained by its use.

CHART I: A CLASSIFICATION OF THE METHODS FOR ABSOLUTE MEASUREMENT OF THE OHM[3]

A. Calorimetric method (Joule).
B. Methods involving an induced electromotive force.
  I. Relative motion of a coil and magnet.
    1. Damping of a magnet (W. Weber).
    2. Rotation of a magnet (Lippman).
    3. Dropping of a magnet (Mengarine).
  II. Rotation of a coil in the earth's magnetic field (the earth inductor).
    1. Earth inductor with rotation through 180° (W. Weber).
    2. Earth inductor with uniform rotation.
      a. Earth inductor with separate tangent galvanometer (W. Weber).
      b. Combined earth inductor and tangent galvanometer (the revolving coil of the B.A. Committee) (Lord Kelvin).
  III. Nonuniform motion of a conductor in the magnetic field of a current.
    1. Damping of a vibrating coil (Nettleton and Lewellyn).
    2. Displacement of a coil (Kirchhoff).
  IV. Uniform motion of a conductor in the magnetic field of a current (generator with air-cored magnets).
    1. Commutating generator.
      a. Average value of generated electromotive force (Rosa).
      b. Maximum value of generated electromotive force (Lippman).
    2. Homopolar generator (Lorenz apparatus) (Lorenz).
  V. Varying currents in a mutual inductance.
    1. Transient currents (Rowland).
    2. Commutated currents.
      a. Sudden reversal of current (Roiti).
      b. Step-by-step reversal of current (Wenner).
    3. Sinusoidal currents.
      a. Intermediary capacitance (Campbell).
      b. Two mutual inductances (Campbell).
      c. Two-phase measured currents (Campbell).
      d. Two mutual inductances with two-phase balanced currents (Wenner).
  VI. Varying currents in a self inductance.
    1. Transient currents (Maxwell).
    2. Commutated currents (Curtis).
    3. Sinusoidal currents.
      a. Intermediary capacitance calibrated by a commutator bridge (Rosa).
      b. Intermediary capacitance calibrated by a resonance bridge (Grüneisen and Giebe).

A. CALORIMETRIC METHOD (JOULE)

The calorimetric method of determining the ohm was of great importance during the early days of absolute measurements, since the electromagnetic laws involved are very different from those used in any other method. It requires not only a determination of the heat generated by a current in a resistance, but also some measurement that will give the value of the current in absolute units. This measurement of current can be made with greater accuracy than a strictly mechanical determination of the mechanical equivalent of heat. Hence this method has generally been used to determine the mechanical equivalent of heat in terms of the electrical units of resistance and current.

[3] This chart is slightly modified from the one given in the book by the author on *Electrical measurements*, McGraw-Hill Book Co. In the book a few methods are discussed in considerable detail.

B. METHODS INVOLVING AN INDUCED ELECTROMOTIVE FORCE

The methods of determining resistance that involve an induced electromotive force may be divided into six general classes, depending on the method of inducing the electromotive force. Each class may be divided and subdivided according to the type of apparatus used.

I. RELATIVE MOTION OF A COIL AND MAGNET

Three methods have been suggested in which an electromotive force is induced by moving a magnet with respect to a coil:

1. Damping of a Magnet (W. Weber)

A small magnet is pivoted or suspended at the center of a coil of wire of known dimensions, the plane of which is vertical and lies in the direction of the reath's field. The period and damping of the magnet are observed both when the circuit through the coil is open and when it is closed. The difference in damping on open and closed circuits is caused by the reaction on the magnet of the current in the coil. This in turn depends on the electromotive force induced in the coil by the swinging magnet and on the resistance of its winding. The resistance of the coil is computed from the period and damping of the magnet, and the dimensions of the coil, without determining the induced electromotive force or the current. This method has been successfully used by several observers, one of whom claims a precision of a part in 10,000.

2. Rotation of a Magnet (Lippman)

The maximum electromotive force induced in a coil by the rotation of a magnet is balanced against the drop in potential over a resistance in which there is a known current. This method seems incapable of giving results of high accuracy.

3. Dropping of a Magnet (Mengarine)

The dropping of a magnet through a coil induces an electromotive force in the coil and the current produced is a function of the resistance. The magnetic field of the current decreases the acceleration of the magnet. The resistance of the coil can be computed from the mass and strength of the magnet and its change in acceleration together with the dimensions of the coil. While this method has been proposed, it does not appear to be capable of giving precise results.

II. ROTATION OF A COIL IN THE EARTH'S MAGNETIC FIELD (THE EARTH INDUCTOR)

In this class are included the methods involving an induced electromotive force that is produced by a coil rotating in the earth's magnetic field. The rotation may be through 180° only or it may be continuous. Both of these methods have been used by several investigators, each of whom has made some modifications of the original method as proposed by W. Weber.

1. Earth Inductor with Rotation through 180° (W. Weber)

The coil of an earth inductor is placed with its plane perpendicular to the horizontal component of the earth's field and suddenly rotated through 180°. The induced electromotive force causes a ballistic deflection of the needle of a tangent galvanometer to which the coil is connected. The value of the earth's field does not need to be known if it is the same at the earth inductor and at the galvanometer. The resistance of the circuit which includes the coil and galvanometer is computed from their dimensions, and the period and damping of the galvanometer magnet.

2. Earth Inductor with Uniform Rotation

The uniform rotation of an earth inductor has two modifications. In one the rotating coil is connected to a tangent galvanometer through a commutator. The galvanometer measures the average value of the induced current. In the other the current induced in the rotating coil is measured by the deflection of a magnet suspended at the center of the coil.

a. Earth inductor with tangent galvanometer (W. Weber).—When a tangent galvanometer is employed with a uniformly rotating earth inductor having a commutator the current through the galvanometer does not change direction but varies from zero to a maximum. Consequently the galvanometer must measure the average current flowing through it. The resistance of the circuit including the rotating coil and galvanometer is determined from the rate of rotation of the coil and the dimensions of the revolving coil and of the coils of the tangent galvanometer.

b. Combined earth inductor and tangent galvanometer (the revolving coil of the B.A. Committee) (Lord Kelvin).—In combining the earth inductor with a galvanometer, a small magnetic needle is suspended at the center of a coil which rotates around a vertical axis. The induced electromotive force produced by rotating the coil in the earth's field causes an alternating current in the coil, which reacts to produce a deflection of the needle. This deflection oscillates slightly but the oscillations are negligibly small if the time of a revolution is much less than the natural period of vibration of the magnetic needle. Since the current is alternating, its value depends on the inductance of the coil as well as on its resistance.

The rotating coil method as just described was used in 1864 in establishing the B.A. unit, which was subsequently found to differ from the absolute ohm by about 1.5 per cent. Since then much more accurate measurements have been made by this method, but in no case has the result been as accurate as a part in 10,000.

III. NONUNIFORM MOTION OF A CONDUCTOR IN THE MAGNETIC FIELD OF A CURRENT

This class of methods is similar to the preceding except that a coil carrying a current replaces the magnet.

1. Damping of a Vibrating Coil (Nettleton and Lewellyn)

The secondary of a mutual inductor is so suspended that it can vibrate about an axis of symmetry, the zero position being the position for zero mutual inductance. With a steady current in the fixed coil, the period and damping of the vibrating coil, both on open and closed circuit, are measured. Then with this same current in the fixed coil, another current having a known ratio to the first is sent through the moving coil producing a measured angular deflection. The mutual inductance is then computed for this angular position of the coils. This gives sufficient data for computing the resistance of the vibrating coil. The method has given results that do not appear to be in error by more than a few parts in 10,000.

2. Displacement of a Coil (Kirchhoff)

A moving coil is connected to a galvanometer that can be used ballistically. There is a known current in a neighboring fixed coil. The moving coil is displaced suddenly, giving a throw to the moving element of the galvanometer. The resistance of the circuit of which the galvanometer is a part is computed from the current in the stationary coil, the dimensions of the coils, and the deflection and constants of the galvanometer. Kirchhoff displaced the coil by giving it a translation in the direction of its axis but most of the other experimenters have used a rotation.

This is the first method ever used for the absolute measurement of resistance but is now of historical interest only.

IV. UNIFORM MOTION OF A CONDUCTOR IN THE MAGNETIC FIELD OF A CURRENT (GENERATOR WITH AIR-CORED MAGNETS)

The electromotive force of a generator, in which the magnetic field is produced by an iron-free coil and in which the armature has a simple geometric form, can be computed from the dimensions of the generator, the rate of motion of the armature, and the current in the coil. Three methods have been used for determining resistance as the ratio of the induced electromotive force to the current in the coil:

1. Commutating Generator

In the case of the commutating generator, a coil or coils rotate in the magnetic field of

the generator, producing an alternating electromotive force in the rotating coil. The rotating coil is connected to the outside circuit through a commutator so that in the outside circuit the current does not change direction. The basic principles involved in the commutating generator are excellent, but no satisfactory experimental test of either of the two modifications has been made. Either modification seems suitable for measurements of high precision.

a. Average value of generated electromotive force (*Rosa*).—If the commutator is of such a type that the connections to the armature are reversed when the electromotive force is zero, the average value of the generated electromotive force must be balanced against the constant drop in potential over a resistance in series with the field coils of the generator. The essential measurements are the dimensions of the coils and the speed of rotation.

b. Maximum value of generated electromotive force (*Lippman*).—This method requires a commutator of such a type that contact is made only when the generated electromotive force is a maximum. This maximum electromotive force can be balanced against the drop in potential over a resistance in series with the field coils of the generator. The essential measurements are the same as in the preceding method.

2. Homopolar Generator (*Lorenz Apparatus*) (*Lorenz*)

A homopolar generator suitable for measuring the absolute value of a resistance is often called a Lorenz apparatus. It consists of an armature in the form of a disk whose axis coincides with the axes of the field coils of the generator. As an example, the disk may be concentric and coaxial with a long solenoid which has an inside diameter larger than that of the disk. When the disk rotates each of its radial elements cuts the magnetic field produced by the current in the solenoid. Hence there is an electromotive force between the axis and circumference of the disk that can be computed from the dimensions of the disk and solenoid, the speed of rotation of the disk, and the current in the solenoid. This induced electromotive force is balanced against the fall in potential in a resistance which is in series with the solenoid. The value of this resistance is thus obtained in absolute units.

The Lorenz method has been used more often than any other, but it has inherent weaknesses, which are discussed in a later section. In the hands of skillful manipulators, an accuracy approaching 10 ppm may be obtained as the average of a considerable number of observations.

V. VARYING CURRENTS IN A MUTUAL INDUCTANCE

The ratio of the electromotive force induced in the secondary of a mutual inductor to the varying current in the primary can be employed to determine the absolute value of a resistance. The mutual inductor must be of such form that its inductance can be computed from its measured dimensions.

1. Transient Currents (*Rowland*)

A transient current is produced in the secondary of a mutual inductor by opening or closing the circuit containing both the primary and a constant electromotive force. During the time that the current is increasing or decreasing in the primary, an electromotive force is induced in the secondary which depends on the mutual inductance and the rate of change of current in the primary. The secondary is connected to a ballistic galvanometer so that the integral of the current produces a deflection of the galvanometer which depends on the resistance of the circuit.

Since this method depends on the reading of a deflection, results more accurate than a part in a thousand cannot be expected. This method has points of similarity with the method of Kirchhoff (III-2) in which one coil is displaced relatively to a second coil carrying a current.

2. Commutated Currents

A commutated current in a circuit containing the primary of a mutual inductance is obtained by periodically reversing the connections to the electromotive force. An alternating electromotive force is induced in the secondary of the mutual inductance. By

means of a second commutator this becomes a series of unidirectional pulses in the external circuit. The average or maximum value of this pulsating electromotive force is compared with the drop in potential over a standard of resistance in the circuit containing the primary.

(*a*) *Sudden reversal of current* (*Roiti*).—The commutator may produce a sudden reversal of the current in the primary so that the induced electromotive force in the secondary is, for each reversal, a short, intense pulse. The comparison of the average electromotive force in the secondary with the maximum potential difference across the resistance in the secondary is difficult.

This method has some promise, but requires an extensive modification of the experimental procedure that has been used before it can be expected to give results of precision.

(*b*) *Step-by-step reversal of current* (*Wenner*).—The commutator and associated apparatus may be so designed that the current in the primary is increased and decreased in steps while the current through a standard resistor in the primary circuit is nearly constant during any half cycle. The induced electromotive force in the secondary is a series of small and frequent pulses. The total electromotive force in the secondary is made more uniform by introducing an electromotive force produced by an induction generator and by the insertion in the secondary circuit of a large, iron-cored inductor. The fall in potential over the standard resistor in the primary is balanced against the average electromotive force in the secondary. The electromotive forces introduced into the secondary by the generator and the inductance do not affect the balance since the integral value of each is zero.

A determination by this method is in progress at the National Bureau of Standards and is giving results of the highest accuracy.

3. *Alternating Currents*

The use of alternating currents in precise electrical measurements has largely developed in the last three or four decades, during which time very few absolute ohm determinations have been made. Several methods have been proposed and given at least a preliminary trial:

(*a*) *Intermediary capacitance* (*Campbell*).—The use of an intermediary capacitance with a mutual inductance involves two different bridges, one of which uses alternating current, the other pulsating current. In the alternating current bridge, the mutual inductance is measured in terms of a capacitance and two resistances. In the pulsating current bridge the same capacitance is measured in terms of a resistance, and the number of pulses per second. By combining the equations of the two bridges, the value of one resistance can be determined in terms of the mutual inductance, the number of pulses per second, and the ratio of two resistances.

The simple theory of this method assumes that the capacitance has the same value for both methods of measurement and that the distributed capacitance of the mutual inductance produces a negligible effect on the computed result. The first assumption is justified if an air capacitor is employed but the second may introduce an error for some types of inductors.

(*b*) *Two mutual inductances* (*Campbell*).—In the method involving two mutual inductances, the secondary of one is connected in series with the primary of the other. Then the electromotive force in the secondary of the one is balanced against a resistance in series with the primary of the other. A diagram of the electrical connections is given in Fig. 1, by means of which the description of the method can be simplified. By different adjustments of resistances and inductances, the current in either the upper or the lower circuit of the right-hand portion of the diagram can be made zero at every instant. In either case, the product of two resistances in these circuits is proportional to the product of the square of the frequency of the alternating current and of the values of two inductances. The method is very direct, but the corrections for the inductances of the resistors are not easy to evaluate. An accuracy of a few parts in a million may be attainable.

(*c*) *Two-phase measured currents* (*Campbell*).—By using a two-phase, alternating current circuit, the electromotive force in the secondary of a mutual inductance having its primary in one phase can be balanced against the drop in potential over a resistance in the second phase. The currents in the two phases have a phase difference of 90° so that the induced electromotive force in the secondary of the mutual inductor can be made equal, at every instant, to the drop in potential over the resistance. The resistance is determined in terms of the frequency, the mutual inductance, and the ratio of the effective values of the currents, which is obtained by the direct measurement of the current in each phase. These currents can not be measured with high precision, so that an accuracy of a part in 10,000 is all that can be expected of this method.

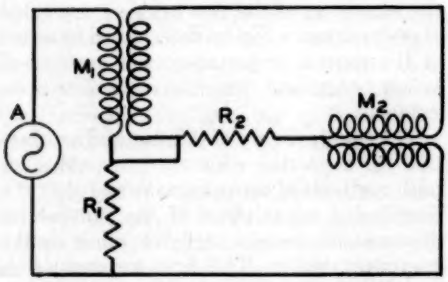

Fig. 1.—The method of Albert Campbell, which employs two mutual inductors in series. As originally described, the resistances R_1 and R_2 and mutual inductances M_1 and M_2 are adjusted to make the current zero in the lower loop of the right-hand side. In the modification by Picard, the adjustments are so made that the current is zero in the upper loop.

(*d*) *Two mutual inductances with two-phase balanced currents* (*Wenner*).—Two mutual inductances can be so used in a two-phase, alternating current circuit that the currents do not need to be measured, provided a double balance is employed. The primary of one inductor is in one of the phases of the alternating current, and that of the other inductor in the opposite phase. The electromotive force in the secondary of each mutual inductance is balanced against the drop of potential in a resistance in the circuit of the opposite phase. The arrangement is symmetrical as shown by the diagram of Fig. 2. The product of the two resistances is proportional to the square of the frequency and to the product of the two mutual inductances. The method has never been given an experimental test but appears capable of giving results of the highest accuracy.

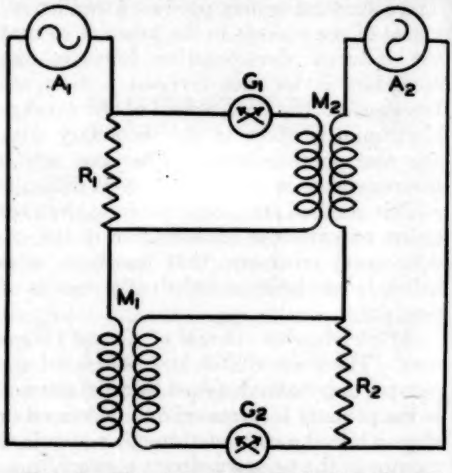

Fig. 2.—The two-phase method using two mutual inductances and requiring two balances. The two windings A_1 and A_2 in the armature of a generator produce alternating electromotive forces which differ in phase by 90°. The resistances R_1 and R_2, and the mutual inductances M_1 and M_2, are adjusted until there is no deflection of either of the vibration galvanometers G_1 and G_2.

VI. VARYING CURRENTS IN A SELF INDUCTANCE

Self inductance methods that employ a varying current can be classified according to the kind of current employed, such as transient current, commutated current, and alternating current. Regardless of the kind of current, the method involves the use of a self inductor of such form that its inductance can be computed from its mechanical dimensions. A single-layer solenoid wound with round wire makes a suitable self inductor, as it can be precisely constructed and accurately measured, and as exact formulas for the calculation of its induct-

ance are available. Since no other form so well fulfills all essential requirements, the single-layer solenoid has been exclusively used in recent determinations of the absolute value of the ohm where a self inductance is involved.

1. Transient Currents (Maxwell)

To employ transient currents with a self inductance, the inductor is placed in one arm of a Wheatstone bridge. There is a key in the battery arm and another in the galvanometer arm. The galvanometer is of the ballistic type. With both keys closed, the bridge is balanced. Then the key in the battery arm is opened, producing a ballistic deflection of the galvanometer. From the period of the galvanometer, the self inductance of the inductor, and the ratio of the resistances in two of the bridge arms, the absolute resistance of a third arm in the bridge can be determined. This method is of historic interest only.

2. Commutated Currents (Curtis)

The use of commutated currents in connection with a self inductance for the absolute measurement of a resistance requires a balanced Wheatstone bridge with one commutator in the battery circuit and another in the galvanometer circuit; the two commutators having a phase difference of approximately 90°. A pulsating current is produced in the galvanometer. A second Wheatstone bridge can be employed to send, through the galvanometer, a direct current which just balances the integral value of the pulsating current. The value of the sum of two resistances is determined in terms of a self inductance, a time, the ratio of two electromotive forces, and the ratio of two resistances. The method appears to be capable of giving results of the highest accuracy.

3. Sinusoidal Currents

All the methods so far proposed for the use of sinusoidal currents with a self inductance have involved the use of an intermediary capacitance. With such a capacitance, two entirely independent measurements must be made, one to measure a resistance in terms of inductance and capacitance, and the second to determine this capacitance in terms of resistance and time. From the two results, the resistance in terms of inductance and time can be computed.

a. Intermediary capacitance calibrated by a commutator bridge (Rosa).—The method requires two bridges; one an alternating current bridge to measure the self inductance in terms of a capacitance and two resistances, the other a pulsating current bridge for measuring the same capacitance in terms of resistance and time. By eliminating the capacitance from the equations of the two bridges, the resistance of one arm is given in terms of the self inductance, the number of pulses per second, and two ratios of resistances.

The simple theory of this method assumes that the residual inductances of the resistors in the alternating current bridge are negligible, and that the capacitance has the same value in the two bridges. To eliminate the effect of the residual inductances, there is substituted for the inductor a conductor of the same resistance but made from high resistivity material and having a form such that its inductance can be computed from its dimensions. In this way the effect of residual inductances in the resistors can be accurately evaluated. The capacitance has the same value in both bridges when the dielectric of the capacitor is either a vacuum or air. This method is capable of giving an accuracy of a few parts in a million.

b. Intermediary capacitance calibrated by a resonance bridge (Grüneisen and Giebe).—This method also requires two bridges, but both use alternating current. The first bridge is the same type as that used in the preceding method; the second is a resonance bridge in which the product of a capacitance and inductance is proportional to the reciprocal of the square of the frequency. The balance of a resonance bridge is affected by extraneous capacitances and by the wave form of the alternating current. While the fundamental principles of this method indicate that it should give a precise result, the experimental difficulties have not yet been overcome.

DISCUSSION OF PRECISION METHODS

There are great differences in the accuracy that can be obtained by the different methods. At the present time an accuracy of ten parts in a million should be the goal in any absolute measurement of the ohm. The characteristics that a method must possess in order to give results of high precision are:

1. The resistance to be measured must be that of a standard resistor having a low temperature coefficient.
2. The method must be a null method or one in which galvanometer deflections are only of secondary importance.
3. The method must give the value of a resistance directly in terms of length, time, and permeability, without an absolute measurement of any derived quantity such as current, power, magnetic induction, or magnetic moment.

Applying these requirements to the methods that have been outlined, we see that they can not be satisfied by the calorimetric method (A), by the methods involving a magnet (B, I), by the methods making use of the earth's magnetic field (B, II), by the methods using a nonuniform motion of a coil (B, III), or by methods requiring transient currents in either a mutual or self inductance (B,V, 1, and B,VI, 1). Of the methods that are not thus eliminated, there is only one, the homopolar generator of Lorenz (B, IV, 2), that does not use either commutated currents or alternating currents. The discussion of precision methods will therefore be made under these headings rather than by following the order given in Chart I.

1. THE HOMOPOLAR GENERATOR

The homopolar generator of Lorenz (B, IV, 2), in which the electromotive force induced in a rotating disk by the magnetic field of a current is balanced against the fall in potential in a resistance carrying the current, fulfills all the requirements for a precision method enumerated in the preceding section. However, there are certain experimental difficulties. The earth's magnetic field induces an electromotive force in the disk, which is added vectorially to that resulting from the current. This difficulty has usually been minimized by making the axis of the disk perpendicular to the direction of the earth's field. In the Lorenz apparatus of the National Physical Laboratory two rotating disks are mounted near the ends of a long shaft. The magnetic field produced in one disk by the current in one set of coils has the opposite direction from the field produced in the other disk by the current in another set of coils. The electromotive forces induced by the current have opposite directions in the two disks, while those induced by the earth's field have the same direction. Hence, the sum of the electromotive forces in the two disks is independent of the earth's field. Another difficulty encountered when using a single disk is the impracticability of making a connection at the center of a disk, but this is avoided by using two disks. An unsolved difficulty results from the heating produced by the friction of the brushes on the rotating disk. This introduces into the circuit of the balancing galvanometer thermal electromotive forces at the brushes. These thermal electromotive forces are very erratic and may be as large as several microvolts, while the induced electromotive forces may be only a thousand times as large. The erratic deflections of the balancing galvanometer must be integrated over a period of several minutes in order to estimate the balance point that the galvanometer would have if thermal electromotive forces were absent. This apparatus at the National Physical Laboratory was used by Smith in 1912 and by Vigoureux in 1936. Each claimed an accuracy of 20 ppm as the average of a large number of measurements. To improve on this accuracy, either the induced electromotive force would have to be increased or the thermal electromotive forces decreased, without introducing any other uncertainty.

2. METHODS EMPLOYING COMMUTATED CURRENTS

Commutated currents or electromotive forces may be used in connection with a mutual inductance, a self inductance, or the armature of an air-cored generator. In the Lippman method (B, IV, 1, b) the maximum value of an induced electromotive force is employed, while in all the other methods the average value is used.

The Lippman method has some of the features of the Lorenz method. The important difference is that the electromotive force is induced in a rotating coil. This coil may have a number of turns, so that the induced electromotive force may be so large that thermal electromotive forces are of no importance. However, the dimensions of the coil while rotating must be accurately determined. This method has not been used for 50 years, but with modern apparatus it should give results of the highest accuracy.

The methods that measure the average value of the commutated currents (B, IV, 1, a; B, V, 2; and B, VI, 2) or electromotive forces have the common difficulty that the current or electromotive force to be measured is made unidirectional by a commutator that reverses the connections to the measuring apparatus when the current or electromotive force is exactly zero. The average value of the pulsating current or electromotive force resulting from the commutation must be compared with a constant current or electromotive force. Probably this can be so well accomplished for all methods that employ commutated currents that each will give results of the highest accuracy. This has been definitely shown at the National Bureau of Standards by Wenner and associates for the method which uses a mutual inductance, but the details of the work have not yet been published.

3. METHODS EMPLOYING ALTERNATING CURRENTS

Alternating current methods have, in recent years, been employed with both mutual and self inductances. At present, more research work is being done to perfect this class of methods than is the case with any other class. An important group in this class employs an intermediary capacitance which is used in an alternating current bridge with an inductance and also in a pulsating current bridge without the inductance. This requires that the capacitance have the same value in the two types of bridges. That this is a correct assumption for an air capacitor appears to be justified since measurements with different frequencies of alternating current and different rates of pulsation for the pulsating current give the same value of the inductance provided the frequencies and the pulsations are so small that extraneous effects are negligible.

Methods belonging to this group are being used at the Physicalisch-Technische Reichsanstalt of Germany, the Electrotechnical Laboratory of Japan, and the National Bureau of Standards. Only two publications giving the details of the experimental procedure have appeared in the last decade. Both of these are by Curtis, Moon, and Sparks, of the National Bureau of Standards, who employed self inductances. The results obtained by using the three inductors described in their first paper showed discrepancies which apparently resulted from slight imperfections in the construction of the inductance standards, although these standards gave evidence of being the equal of any that had been produced elsewhere. In the second paper, they describe a self inductor which has such uniform dimensions that the uncertainty in the computed inductance was much less than that for their previous inductors. The electrical measurements have been improved, so that the final result appears to be in error by only a few parts in a million. It seems probable that equally good results can be obtained with a mutual inductance, but Yoneda who is using one at the Electrotechnical Laboratory has not yet published the details of his work.

The method of Campbell (B, V, 3, b), which uses two mutual inductances (Fig. 1), requires a very stable frequency and an alternating current for which the wave form

is very nearly sinusoidal. In the form as originally proposed, some copper resistances have to be evaluated. Picard's modification avoids this difficulty, but requires the evaluation of both a self and a mutual inductance. In any case there are a number of correction terms depending on the residual inductances of resistors and the capacitances of each part of the apparatus to other parts and to earth. If the apparatus is suitably designed and properly operated, either modification of this method will give results of high accuracy.

A determination was recently made at the National Physical Laboratory by Hartshorn and Astbury using Campbell's original method. They estimate that the error in their electrical measurements is less than 5 ppm, while there is an uncertainty in the value of the computed inductance of their standard mutual inductor of 10 ppm. A determination using the Picard modification has recently been made at the Laboratoire Central d'Electricité by Jouaust, Picard, and Héron. They had so much difficulty in constructing their inductor and in making precise mechanical measurements upon it that their result is not of high accuracy.

Wenner's two-phase method (B, V, 3, d) also seems capable of giving results of high accuracy. It requires the simultaneous balancing of two circuits. (See Fig. 2.) The wave form of the current in both phases must be nearly sinusoidal, the frequency constant, and the phase angle between the currents must be known. It is a promising method that has never been given an experimental test.

In Table 1 is given in chronological order a list of all the important results on the absolute ohm. All results have been reduced, when necessary, to the length of the mercury column, 1 mm² in cross section and maintained at 0°C., which would give a resistance of one absolute ohm. This reduction has been necessary for many of the results that were obtained between 1875 and 1885, when investigators usually gave the value of the B.A. unit in absolute ohms. These results have been converted to the length of the standard mercury column by using the values obtained in contemporary measurements on the resistivity of mercury. Also the reduction has been required for all results obtained during the last two decades when investigators have expressed their results in terms of the international ohm as maintained by their national laboratory. These results can readily be converted to mean international ohms as a result of the international comparisons that have been made at periodic intervals. The mean international ohm is the mean of the units of the national laboratories. Hence, recent results have been reduced to the same basis as the earlier results by assuming that the mean international ohm is represented by a column of mercury at 0°C., which has 1 mm² cross section[4] and a length of 106.3000 cm.

The bibliography included in this review has been prepared not only to give references to the different determinations but also to present the salient facts connected with the work.

This paper is a historical study of an important phase of physics. The question of the present relationship between the absolute ohm and international ohm has been intentionally omitted. The International Committee of Weights and Measures decided in 1939 that the most probable value of this relationship is

1 mean international ohm
= 1.00048 absolute ohms.

A more definite value will be promulgated by this committee when conditions warrant. A committee of the National Research Council has under consideration the question of recommending a value to be used in the United States.

[4] The specifications for the mercury ohm as prepared by the Chicago Electrical Congress of 1893 give the mass of mercury instead of the cross section of the tube. This was adopted because the cross section is experimentally determined from the mass and density of the mercury and the length of the tube. By specifying mass, a knowledge of the density of mercury and of the cross section of the tube is not required. However, the Congress intended that the cross section of the tube should be 1 mm².

TABLE 1.—RESULTS OF ABSOLUTE DETERMINATIONS OF THE OHM

Year	Author	Principle of method	Number in chart	Results expressed in length of Hg column (cm) having cross section of 1 mm²		Remarks
				Published	Deduced or corrected	
1849	Kirchhoff	Displacement of a coil	B, III, 2		140	Results expressed in terms of resistivity of copper.
1851	W. Weber	Earth inductor	B, II, 1		91	Results expressed in Jacobi's units.
		Damping of magnet	B, I, 1		91	
1862	W. Weber	Earth inductor	B, II, 1		98	
1863	Maxwell, Stewart, Jenkin	Rotating coil in earth's field	B, II, 2, b		105.02 or 104.70	Authors give magnitude of difference from 1864 result but not sign.
1864	Maxwell, Stewart, Jenkin	As above	B, II, 2, b	104.56	104.86	Results used to establish the B.A. unit. Corrected value by Jenkin in 1871.
1867	Joule	Generation of heat	A		105.91	Results expressed as 1 B.A. unit = 0.98953 ohm.
1870	Kohlrausch	Earth inductor	B, II, 1	102.9		
1873	Lorenz	Rotating disk	B, IV, 2	107.1		
1877	H. F. Weber	Damping of magnet	B, I, 1	104.79		A careful research.
		Mutual inductance with transient currents	B, V, 1	104.67		Result confirms that of B.A. Committee.
		Generation of heat	A	104.71		
1878	Rowland	Mutual inductance, transient currents	B, V, 1		105.7	Results expressed as 1 B.A. ohm = 0.9911 earth quadrant/sec.
1881	Rayleigh, Schuster	Rotating coil in earth's field	B, II, 2, b		105.8	Author's result 1 B.A. ohm = 0.9893 earth quadrant/sec.
1882	Dorn	Damping of magnet	B, I, 1	105.46		
1882	Rayleigh	Rotating coil in earth's field	B, II, 2, b		106.23	Author's result 1 B.A. unit = 0.98651 earth quadrant/sec and 1 mercury unit = 0.95418 B.A. unit.
1882	H. Weber	Rotating coil in earth's field	B, II, 2, b		106.14	Result given as 1 B.A. unit = 0.9877 ohm.
1883	Glazebrook, Dodds, Sargent	Mutual inductance, transient currents	B, V, 1		106.22	Result given as 1 B.A. unit = 0.98665 ohm.
1883	Rayleigh, Sidgwick	Rotating disk	B, IV, 2	106.214		Also states 1 B.A. unit = 0.98677 $\times 10^{-9}$ C.G.S.
1884	Wiedemann	Earth inductor	B, II, 1	106.19		
1884	H. F. Weber	Earth inductor	B, II, 1	105.31		
1884	Himstedt	Mutual inductance, commutated currents	B, V, 2	105.98		
1884	Mascart, deNerville, and Benoit	Earth inductor	B, II, 1	106.33		Authors state that result with mutual inductance is the more reliable.
		Mutual inductance transient currents	B, V, 1	106.30		
1884	Roiti	Mutual inductance, commutated currents	B, V, 2	105.896		
1884	Wild	Damping of magnet	B, I, 1	106.027	106.2	Corrected by Dorn.
1884	Baille	Damping of magnet	B, I, 1	105.7		Estimated results accurate to 1 per cent.
1884	Rowland, Kimball	Mutual inductance, transient currents	B, V, 1	106.34		Preliminary results.
		Rotating disc	B, IV, 2	106.32		
1885	Fletcher	Generation of heat	A		105.90	Results expressed as 1 B.A. unit = 0.9104 earth quadrant/sec.
1885	Lorenz	Rotating disc	B, IV, 2	105.93		
1885	Himstedt	Mutual inductance commutated currents	B, V, 2	106.08		
1888	Kohlrausch	Damping of magnet	B, I, 1	106.32		
1889	Dorn	Damping of magnet	B, I, 1	106.243	106.245	A very careful determination. Correction by author.
1889	Duncan, Wilkes, Hutchinson	Rotating disk	B, IV, 2	106.34		Also state: 1 B.A. unit = 0.9863 ohm.
1890	Wuilleumier	Commutating generator. Maximum electromotive force	B, IV, 1, b	106.267	106.32	Corrected by Leduc.

TABLE 1.—RESULTS OF ABSOLUTE DETERMINATIONS OF THE OHM—*Continued*

Year	Author	Principle of method	Number in chart	Results expressed in length of Hg column (cm) having cross section of 1 mm²		Remarks
				Published	Deduced or corrected	
1890	Jones	Rotating disk	B, IV, 2	106.307		
1891	Wiedemann	Earth inductor	B, II, 1	106.265	106.249	Recomputed by Peter.
1894	Jones	Rotating disk	B, IV, 2	106.326		Estimates accuracy as 1 in 10,000.
1895	Himstedt	Mutual inductance commutated currents	B, V, 2, a	106.282		
1897	Ayrton, Jones	Rotating disk	B, IV, 2		106.274	Result expressed as 1 Board of Trade ohm = 1.00026 true ohms.
1899	Guillet	Mutual inductance, commutated currents	B, V, 2, a	106.20		
1912	Campbell	Mutual inductance, sinusoidal currents				Results in N.P.L. units. Author's
		a. Two-phase	B, V, 3, c		106.327	estimate of error is 1 in 10,000.
		b. Intermediary condenser	B, V, 3, a		106.329	Preliminary.
1914	Smith	Rotating disk	B, IV, 2	106.245		Author's estimate of error is 4 in 100,000.
1920	Grüneisen, Giebe	Self inductance, sinusoidal currents with intermediary condenser	B, VI, 3, a	106.246		Result given is 1 int ohm = 1.00051 ± 0.00003 abs ohms
1925	Campbell	Two mutual inductances	B, V, 3, b	106.246		Author's estimate of error is 1 in 10,000.
1936	Curtis, Moon, Sparks	Self inductance with intermediary capacitance	B, VI, 3, a		106.2519	Result expressed as 1 NBS int ohm = 1.000450 abs ohms.
1937	Vigoureux	Rotating disk	B, IV, 2		106.2471	Result expressed as 1 NPL int ohm = 1.000495 abs ohms.
1937	Yoneda	Mutual inductance with intermediary capacitance	B, V, 3, a		106.2506	Result expressed as 1 ETL int ohm = 1.000455 ± 20 abs ohms.
1937	Hartshorn, Astbury	Two mutual inductances in series	B, V, 3, b		106.2464	Result expressed as 1 NPL int ohm = 1.000501 abs ohms.
1938	Jouaust, Picard, Héron	Two mutual inductances in series	B, V, 3, b		106.245	Result expressed as 1 LCE int ohm = 1.00052 abs ohms.
1938	Curtis, Moon, Sparks	Self inductance with intermediary capacitance	B, VI, 3, a		106.2488	Result expressed as 1 NBS int ohm = 1.000479 abs ohms.
1939	Zickner	Self inductance with intermediary capacitance	B, VI, 3, a		106.241	Result expressed as 1 PTR int ohm = 1.00051 abs ohms.
1939	Wenner, Thomas, Cooter, Kotter	Mutual inductance with commutated currents	B, V, 2, b		106.2482	Result expressed as 1 NBS int ohm = 1.000485 abs ohms.

BIBLIOGRAPHY ON ABSOLUTE OHM MEASUREMENTS

(All titles are given in English)

1849. G. R. KIRCHHOFF.

Determination of the constant on which the intensity of the induced current depends. Ann. Phys. Chem. **76**: 412.

This is the first determination of a resistance in terms of mechanical units and permeability. The primary purpose of the article was to determine the permeability of air in terms of the resistivity of copper. The final conclusion was, "The constant ϵ equals unity if the unit of velocity is 1000 ft/sec and the unit of resistance is a copper wire of a square line cross section and a length of 0.434 inch." The Prussian/foot = 31.4 cm. 144 lines = 12 inches = 1 foot.

1851. WILHELM WEBER.

Measurements of electrical resistance according to an absolute standard. Ann. Phys. Chem. **82**: 337. (Translated in Phil. Mag. (4) **22**: 226. 261, 1861.)

Outlined a complete system of electric units based on the mechanical units. Gave two methods for determining the absolute ohm; one the earth inductor rotating through 180° and the other the damping of a magnet. The two results agree to 0.3 per cent. Results were given in Jacobi's units and have been reduced to the length of a mercury column by values given in 1864 B.A. Report. See complete reference below (1863–64).

1862. WILHELM WEBER.

On electrical measurements. Abh. Math. Klasse Göttingen Ges. **10**: 3. (Also printed separately under the title *Zur Galvanometrie*, Göttingen, 1862.)

A very long article dealing with many phases of electrical measurements. States result on ohm (p. 58) as the Siemens standard resistance = 10257000 meter/second. If this refers to a Siemens Einheit, then the length of the mercury column is 98 cms for an absolute ohm. The B.A. report of 1865 gives the value as 96. The author notes the unsatisfactory state of resistance standards.

1863–64. J. CLERK MAXWELL, BALFOUR STEWART, and FLEMING JENKIN.

Description of an experimental measurement of electrical resistance made at King's College. Rep. British Assoc. **33**: 163, 1863; **34**: 345. 1864. (Also in Reports of the Committee on Electrical Standards of B.A. edited by F. E. Smith, pp. 140, 166.)

Results used to establish the B.A. unit of resistance. Individual results differ by several per cent. There was an uncertainty of 2 per cent in the mercury resistors then available while the probable error of the 1864 result was only 0.1 per cent.

1867. J. P. JOULE.

Determination of the dynamical equivalent of heat from the thermal effect of electric currents. Rep. British Assoc. **37**: 474. (Also in Reports of Electrical Standards Committee of B.A. p. 256, 1913; edited by F. E. Smith.)

Makes experiments with both mechanical and electrical calorimeter. Does not emphasize the result on the ohm.

1870. F. KOHLRAUSCH.

Determination of the Siemens unit of resistance in absolute measure. Nachr. Ges. Wiss. Göttingen (abstract) **10**: 513. (Also Ann. Phys. Chem., Erganzungs Band 6, p. 1, 1874; translation: Phil. Mag. (4) **47**: 294, 342. 1874.)

Uses the same apparatus as employed by W. Weber in 1862. Rowland, in Phil. Mag. (4) **50**: 161. 1875, suggested a modification of the theory which might change the result by 2 per cent.

1873. L. LORENZ.

The electrical resistivity of mercury in absolute measure. Ann. Phys. Chem. **149**: 251.

First use of the rotating disk as a homopolar generator. The resistance measured, about 0.002 ohm, was too small to compare accurately with a mercury column 1 meter long.

1877. H. F. WEBER.

Electromagnetic and calorimetric absolute measurements: The absolute value of Siemens unit of resistance in electromagnetic measure; the relation between current-work and the heat-evolution in stationary galvanic currents; and the absolute values of some constant hydroelectromotive forces in electromagnetic measure. Natur. Ges. Zurich, Vierteljahrsschr. **22**: 273. (Translation in Phil. Mag. (5) **5**: 30, 127, 189. 1878.)

Used three methods and concluded that all gave the same result. His value agreed with that of the B.A. Committee.

1878. HENRY A. ROWLAND.

Research on the absolute unit of resistance. Amer. Journ. Sci. **115**: 281, 325, 430. (Also Collected Papers, p. 145.)

First experimenter to show definitely that the B.A. unit was in error by more than 1 per cent.

1880. W. WEBER and F. ZÖLLNER.

An apparatus for use in absolute measurements in electrodynamics with practical applications. Ber. Sächs. Ges. Wiss. Math-Phys. Klasse **32**: 77.

Work interrupted by death of Zöllner. Completed in 1884 by G. Wiedemann.

1881. LORD RAYLEIGH and A. SCHUSTER.

Determination of the ohm in absolute measure. Proc. Roy. Soc. **32**: 104.

Used the method employed by Maxwell, Stewart, and Jenkin, with much of their apparatus. Improved method of obtaining inductance of coil. Used water motor for driving coil.

1881. G. CAREY FOSTER.

Account of preliminary experiments on the determination of the ohm in absolute measure. British Assoc. Rep. **51**: 423. (Also Reports of Committee on Electrical Standards, p. 296. 1913; Electrician **7**: 266. 1881.)

Described a method in which the electromotive force induced in a coil rotating in the earth's field is balanced against the fall of potential of a known current in the resistance to be measured. Preliminary results check B.A. ohm.

1882. LORD RAYLEIGH.

Experiments to determine the value of the British Association unit of resistance in absolute measure. Phil. Trans. Roy. Soc. **173** (pt. 2): 661.

Used same method as in previous experiment but constructed new apparatus. Gave value in B.A. units. To convert to mercury column, see Rayleigh and Sidgwick on the Specific Resistance of Mercury, Proc. Roy. Soc. **34**: p. 27. 1882.

1882. G. LIPPMAN.

The methods to be employed for the determination of the ohm. Journ. Physique (2) **1**: 313.

Proposed a method for balancing the maximum electromotive force of a continuously rotating earth inductor against the fall in potential in a resistance produced by a measured current. No results.

1882. J. JOUBERT.

Method for determination of the ohm. Compt. Rend. Acad. Sci. **94**: 1519.

Suggested a method in which (1) the effective electromotive force induced in a coil rotating in the earth's field is measured by an electrometer, and (2) the drop in potential over a resistance through which a known current is flowing is measured by the same electrometer. No results.

1882. HEINRICH WEBER.

The rotation inductor, its theory and its use for the determination of the ohm in absolute measure. (Published in book form by Teubner, Leipzig, 1882, translated in Phil. Trans. Roy. Soc. **174** (pt. 1): 223. 1883.)

Used a rotating coil in the earth's field with axis horizontal.

1882. E. DORN.

The determination of the Siemens unit in absolute measure. Ann. Phys. Chem. **253**: 773.

Use a method that depended on the damping of a magnet.

1882. A. ROITI.

Method for the determination of the ohm. Atti. Acc. Sci. Torino **17**: 588. (Also Nuovo Cimento **12**: 60. 1882.)

Outlined method for using a commutated current with a mutual inductance. No result.

1883. R. T. GLAZEBROOK, J. M. DODDS, and E. B. SARGENT.

Value of the British Association unit of resistance. Phil. Trans. Roy. Soc. **174** (pt. 1): 223.

Worked under direction of Lord Rayleigh.

1883. LORD RAYLEIGH and MRS. H. SIDGWICK.

Experiments, by the method of Lorenz, for the further determination of the absolute value of the British Association unit of resistance. Phil. Trans. Roy. Soc. **174** (pt. 1): 295. (Abstract in Proc. Roy. Soc. **34**: 438. 1883.)

This research was very carefully planned and skillfully executed.

1883. M. BRILLOUIN.

Methods for the determination of the ohm. Comp. Rend. Acad. Sci. **96**: 190.

Suggested the use of alternating currents in connection with a mutual inductance. No results.

1883. J. FROELICH.

On the determination of the ohm by dynamical methods. Ann. Phys. Chem. **255**: 106.

Gave a rough outline of a method that involves the rotation of one coil with respect to another. The important contribution is a formula for computing mutual inductance.

1884. G. WIEDEMANN.

On the determination of the ohm. Abh. Berlin Akad., Phys. Kl., **3**: 75. Lumière Electrique **12**: 419.

Continued work of Weber and Zöllner (1880), which was interrupted by Zöllner's death. Value of 106.265 cm of mercury given in Abh. Berlin Akad. Corrected to 106.19 in Lumière Electrique.

1884. H. F. WEBER.

The absolute value of the Siemens mercury unit and the magnitude of the ohm in terms of a mercury column. (Published in book form by Zürcher & Furrer of Zürich.)

Observed ballistic throw of a tangent galvanometer produced by the rotation of an earth inductor through 180°.

1884. F. HIMSTEDT.

On a method for determining the ohm. Ann. Phys. Chem. **258**: 281.

Published a method of using a mutual inductance with commutated currents but gave no result on the ohm. Fundamental principle same as that of Roiti.

1884. M. MASCART, F. DE NERVILLE, and R. BENOIT.

Determination of the ohm and its value in terms of a column of mercury. Ann. Phys. Chem. (6) **6**: 5. (Abstract in Journ. Physique (2) **3**: 230. 1884.)

Used two methods: One an earth inductor with galvanometer and the other a variable mutual inductor substituted for the earth inductor.

1884. A. ROITI.

Determination of the electrical resistance of a wire in absolute measure; preliminary note. Nuova Cim. (3) **15**: 97. (Also Atti Accad. Sci. Turino **19**: 643. 1884.)

Used a mutual inductance with commutated current.

1884. G. MENGARINI.

Method for the determination of the ohm in absolute measure. Atti Accad. Lincei (3) **8**: 318.

Proposed a method by which the resistance of a horizontal coil may be measured from the decrease in acceleration of a magnet falling through the coil and the electrical energy induced in the coil. No results.

1884. H. WILD.

Determination of the value of the Siemens unit of resistance in absolute electromagnetic units. Ann. Phys. Chem. **259**: 665. (Original publication in Trans. St. Petersburg Acad.)

Original Value of 106.027 later corrected by Dorn (Ann. Phys. Chem. **271**: 273. 1888) to 106.2.

1884. J. B. BAILLE.

On the determination of the ohm by the method of the damping of a moving magnet. Ann. Télégr. **11**: 89, 131.

1884. H. A. ROWLAND and A. S. KIMBALL.

Report in Philadelphia Electrical Congress, p. 41. 1884; Electrical World **6**: 27. 1885.

Reporter's account of Rowland's paper before the British Association in La Lumière Electrique **26**: 188. 1887. Second article reprinted in Rowland's Collected Works, p. 239. A personal letter from one of Rowland's assistants stated that, in disassembling the apparatus, Rowland discovered two pieces of iron in the frames on which the coils were wound. That made him uncertain as to the results, so that only preliminary values have been published.

1885. L. B. FLETCHER.

A determination of the B.A. unit in terms of the mechanical equivalent of heat. Phil. Mag. (5) **20**: 1; Amer. Journ. Sci. **130**: 22.

Work done at Johns Hopkins University, Baltimore, Md., using Rowland's value of the mechanical equivalent of heat.

1885. L. LORENZ.

Determination of the electrical resistance of a mercury column in absolute electromagnetic units. Ann. Phys. Chem. **261**: 1.

Gave more attention to the mercury ohm than to the absolute measurement.

1885. F. HIMSTEDT.

A determination of the ohm. Ann. Phys. Chem. **262**: 547. (Translation in Phil. Mag. (5) 20: 417. 1885; Sitz. Ber. Akad. Wiss. Berlin, pt. 2; 753. 1885. Corrections in Ann. Phys. Chem. **264**: 338, 1886; **267**: 617. 1887.)

Used same method as in 1884. Value of 105.98 finally corrected to 106.08.

1888. F. KOHLRAUSCH.

On the electrical resistivity of mercury. Ann. Phys. Chem. **271**: 700. (Also Collected Works, vol. 1, p. 773.)

A very elaborate set of experiments giving considerable attention to the mercury ohm.

1889. E. DORN.

A determination of the ohm. Ann. Phys. Chem. **272**: 22, 398.

A very elaborate determination with observations running over more than a year. Compared resistances with the mercury ohm of Kohlrausch.

1889. L. DUNCAN, G. WILKES, and C. T. HUTCHINSON.

A determination of the value of the B.A. unit of resistance in absolute measure by the method of Lorenz. Phil. Mag. (5) **28**: 98.

Used Rowland's apparatus. Result in B.A. units and in terms of the mercury column as obtained from work of Hutchinson and Wilkes, Phil. Mag. (5) **28**: 17. 1889.

1890. M. H. WUILLEUMIER.

Determination of the ohm by the electrodynamic method of M. Lippman. Journ. Phys. **9**: 220.

Rotated a coil inside a long solenoid, comparing the maximum induced electromotive force with the drop in potential over a resistance in series with the solenoid. Leduc (Compt. Rend. Acad. Sci. **118**: 1246. 1894) corrected result for finite length of solenoid.

1890. J. V. JONES.

On the determination of the specific resistance of mercury in absolute measure. Phil. Trans. **182**: 1.

Mercury contained in a paraffin trough. Method of rotating disk used for resistance measurements.

1891. G. WIEDEMANN.

On the determination of the ohm. Ann. Phys. Chem. **278**: 227, 425.

Completion of the work of W. Weber and Zöllner for which there was a first report in 1884. Peter (Ber. Versich. Akad. Wiss. Leipzig, Math.-phys. Kl., **46**: 139. 1894) corrected result by considering finite cross section of coil of tangent galvanometer.

1894. J. V. JONES.

On the determination of the international ohm in absolute measure. Rep. British Assoc. Adv. Sci., 1894, p. 123. (Also Rep. Comm. of B.A. on Electrical Standards, p. 489, 1913.)

Used same apparatus as in 1890.

1895. F. HIMSTEDT.

On an absolute resistance measurement. Ann. Phys. Chem. **290**: 305.

Used a mutual inductance with commutated currents. Measured primary and secondary currents by a tangent galvanometer. The mutual inductance consisted of a coil within a solenoid. Employed two solenoids and several coils. Results vary by a few parts in 10,000.

1897. W. E. AYRTON and J. V. JONES.

On a determination of the ohm made in testing the Lorenz apparatus of the McGill University, Montreal. Rep. British Assoc. Adv. Sci., 1897, p. 212. (Also Rep. Comm. of B.A. on Electrical Standards, p. 567. 1913.)

Result expressed in Board of Trade ohms; was later reduced to mercury ohm by F. E. Smith (Coll. Res. of NPL **11**: 209. 1914. Reduction on p. 217).

1899. A. GUILLET.

Direct determination of an absolute kilohm. Journ. Physique (3) **8**: 471.

Commutated currents were used with a mutual inductance and differential galvanometer. Apparatus poorly described.

1908. E. B. ROSA.

A new method for the absolute measurement of resistance. Bull. Bur. Standards **5**: 499.

Gave theory of a method using a commutating generator. No results.

1912. ALBERT CAMPBELL.

On the determination of the absolute unit of resistance by alternating current methods. Proc. Roy. Soc. London **87**: 391.

Used mutual inductance with two different methods, (1) two-phase measured currents, and (2) intermediary condenser. Purpose was to investigate methods rather than obtain an exact result.

1914. F. E. SMITH.

Absolute measurement of a resistance by a method based on that of Lorenz. Phil. Trans. Roy. Sci. **214-A**: 27; NPL Coll. Res. **9**: p. 209.

This determination, made at the National Physical Laboratory, is more precise than any that preceded it. Every source of error was checked. Almost simultaneously (see Report of National Physical Laboratory for 1912, p. 39) a comparison of the resistance standards used was made with the mercury ohm.

1920. E. GRÜNEISEN and E. GIEBE.

A new determination of the absolute unit of electrical resistance. Wiss. Abh. P.T.R. Charlottenburg **5**: 1. 1921. (Abbreviated article in Ann. Phys. **368**: 179. 1920.)

A determination using self inductance and alternating current. Accuracy compares with that of Smith. Measurements completed in 1914, but publication delayed by war. A direct comparison was made with Smith's resistance standards. Result showed that the error of a mercury ohm determination is of the same order as the error in an absolute determination.

1925. A. CAMPBELL.

On the determination of resistance in terms of mutual inductance. Proc. Roy. Soc. London **107**: 310.

Simple experiments to test feasibility of the method that employs two mutual inductances in series.

1936. H. L. CURTIS, C. MOON, and C. M. SPARKS.

An absolute determination of the ohm. Journ. Res. Nat. Bur. Standards **16**: 1.

Three different self inductors were used.

1937. J. E. P. L. VIGOUREUX.

Determination of the ohm by the method of Lorenz. Coll. Res. NPL **24**: 209. 1936–7.

Used apparatus described by F. E. Smith (1914) but remeasured the mechanical dimensions.

1937. RINKICHI YONEDA.

Absolute determination of electrical resistance. Proc. Verb. Comm. Int. Poids et Mes. (2) **18**: 178.

Used alternating currents with a mutual inductance. An intermediary capacitance was employed.

1937. L. HARTSHORN and N. F. ASTBURY.

The absolute measurement of resistance by the method of Albert Campbell. Phil. Trans. Roy. Sci. **236A**: 423.

An extremely careful determination. Estimated uncertainty is 5 ppm for the electrical measurements and 10 ppm for the value of the computed inductance. There are numerous small corrections.

1938. R. JOUAUST, M. PICARD, and R. HÉRON.

Determination of the unit of resistance in the CGS electromagnetic system. Bull. Soc. Franc. Elec. (5) **8**: 1.

An extensive investigation, but the apparatus available gave results accurate only to parts in a hundred thousand. Used Piccard's modification of Campbell's method (Compt. Rend. Acad. Sci. 189: 125. 1929).

1938. H. L. CURTIS, C. MOON, and C. M. SPARKS.

A determination of the absolute ohm, using an improved self inductor. Journ. Res. Nat. Bur. Standards 21: 375.

Used a self inductor of superior construction.

1939. G. ZICKNER.

On the condition of the experiments for the determination of the international ohm in absolute units. MS. Report to the International Committee of Weights and Measures. Not yet published.

1939. F. WENNER, J. L. THOMAS, I. L. COOTER, and F. R. KOTTER.

Preliminary report on the absolute measurement of a resistance based on the reversal of a direct current in a mutual inductance. A report sent to the International Committee of Weights and Measures in December, 1938.

Apparatus not described.

1940. H. L. CURTIS and L. W. HARTMAN.

A dual bridge for the measurement of self inductance in terms of resistance and time. Journ. Res. Nat. Bur. Standards 25: 1.

An experimental test of the method for using commutated currents with a self inductance.

MEDICAL ENTOMOLOGY.—*Experimental transmission of endemic typhus fever by the sticktight flea,* Echidnophaga gallinacea.[1]

JOSEPH E. ALICATA, Hawaii Agricultural Experiment Station, University of Hawaii.

In 1931, Dyer, Rumreich, and Badger (1, 2) first demonstrated the natural infection of the rat fleas *Xenopsylla cheopis* and *Ceratophyllus fasciatus* with endemic typhus. The fleas were collected from wild rats trapped at typhus foci in Baltimore, Md., and Savannah, Ga. In 1931 and 1932 Dyer (3, 4) and collaborators were also able to demonstrate experimentally the susceptibility of these fleas to endemic typhus. In 1932, Mooser and Castaneda (5) reported experimental transmission of this disease by the following fleas: *Leptopsylla musculi, Ctenocephalus* (=*Ctenocephalides*) *felis, C. canis,* and *Pulex irritans.* Blanc and Baltazard (6) also reported *P. irritans* as a carrier of endemic typhus. In 1933 Workmann (7) reported the experimental transmission of endemic typhus by *Xenopsylla astia.*

The present paper deals with the experimental transmission of endemic typhus by the sticktight flea *Echidnophaga gallinacea.* So far as is known to the writer, the susceptibility of this flea to endemic typhus has not previously been reported.[2] The finding is of considerable interest in the Hawaiian Islands since the flea is of common occurrence on rats as well as on dogs, cats, mongooses, and chickens. According to a survey conducted by Eskey (8), *E. gallinacea* has been found on 13 percent of the rats trapped in the city of Honolulu. This flea frequently infests rats in large number, Eskey having shown that about 52 percent of the fleas collected on rats of the island of Oahu were found to be sticktight fleas.

EXPERIMENTAL DATA

On April 12, 1941, about 150 sticktight fleas were obtained from the ears of a dog in Honolulu. In order to be assured of absence of natural infection, 50 fleas were emulsified in physiological saline solution

[1] Published with the approval of the director as Technical Paper No. 93, Hawaii Agricultural Experiment Station. This study has been conducted through special funds appropriated by the Public Health Committee, Chamber of Commerce of Honolulu. Received October 6, 1941.

The writer is indebted to Drs. R. E. Dyer and N. H. Topping, of the National Institute of Health, U. S. Public Health Service, Washington, D. C., for supplying the Wilmington strain of endemic typhus used in the experiments reported in this paper. Acknowledgment is made also to Dr. R. D. Lillie, of the National Institute of Health, for the histological examination of the brain of one of the experimental animals.

[2] After this paper was sent to the editor, the writer noted a recent publication by Dr. G. D. Brigham (Pub. Health Rep. 56(36): 1803–1804. Sept. 5, 1941) reporting the recovery of typhus virus from sticktight fleas (*E. gallinacea*) removed from two rats collected in Georgia. This report adds to the public health importance of these fleas.

and injected intraperitoneally into two guinea pigs. Neither of these animals developed any signs of typhus fever during a period of two weeks, nor was either found immune following experimental inoculation with a known endemic typhus virus (Wilmington strain) obtained from National Institute of Health, U. S. Public Health Service. The remaining fleas were placed on the body of a white rat freshly inoculated with 2.5 cc of testicular washings from a guinea pig experimentally infected with the Wilmington strain of endemic typhus. Two guinea-pig controls, injected with the same inoculation, developed typical fever and scrotal reaction.

Most of the fleas that were placed on the rat attached themselves in a short time to various parts of the body particularly around the ears, eyes, and face. Thirteen days after the experimental infestation the rat was killed by a blow on the head, and 82 fleas were carefully removed. These fleas were placed into a small test tube overnight. The following morning the fleas and eggs were removed from the test tube, and all the feces of the fleas found adhering to the walls of the test tube were taken up in saline solution and inoculated intraperitoneally into a male guinea pig (No. 53). At the same time all the fleas were emulsified in saline solution and inoculated intraperitoneally into a male guinea pig (No. 54).

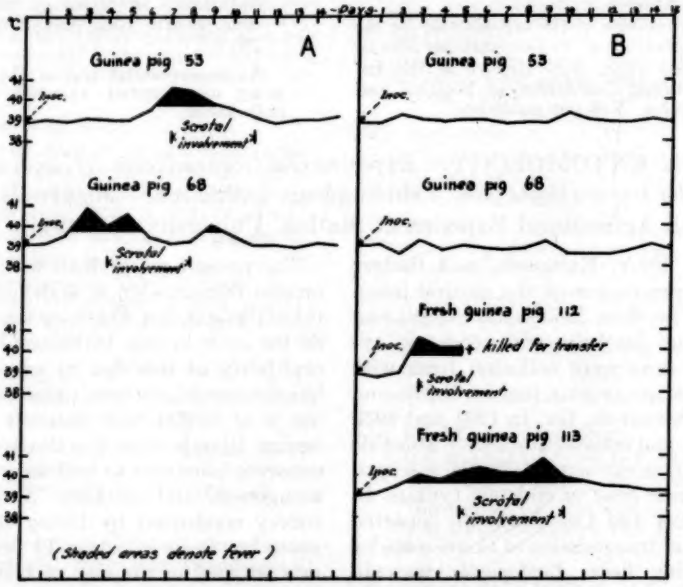

Fig. 1.—Cross immunity test: Daily temperature records of (A) guinea pigs inoculated with virus recovered from the sticktight fleas; (B) guinea pigs inoculated with the known endemic typhus virus (Wilmington strain).

A few days after these inoculations, both guinea pigs developed clinical typhus.

Guinea pig 53 was later found to be immune when inoculated with the Wilmington strain of endemic typhus (Fig. 1). Guinea pig 54 (first generation) was killed on the second day of fever and testicular involvement, and testicular washings from this animal were inoculated into guinea pig 57 (second generation). From this animal the strain was passed to three guinea pigs, 68, 69, and 70 (third generation), and later the strain was passed from guinea pig 69 to

guinea pig 97 (fourth generation). All the guinea pigs involved in the passage of the virus developed clinical endemic typhus. One of the animals (No. 68) of the third generation was then tested for susceptibility to endemic typhus and was found immune. Blood cultures made from the guinea pigs were uniformly negative. Scrapings from the tunica vaginalis of these animals also revealed intracellular rickettsial bodies.

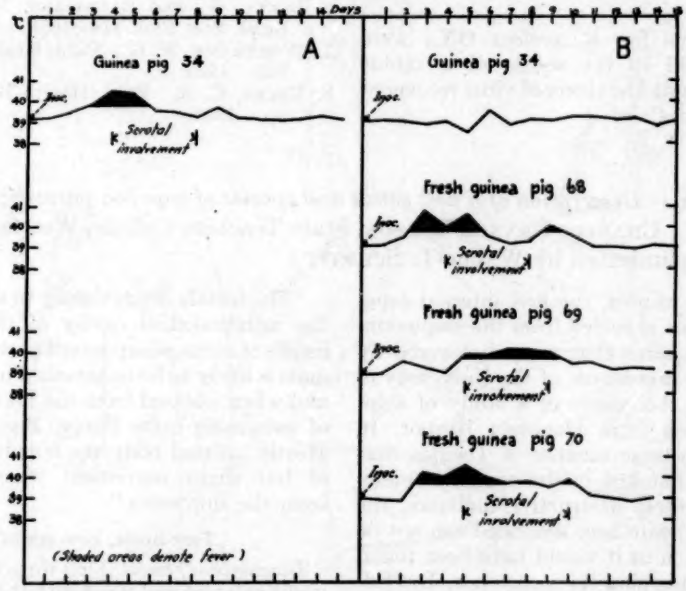

Fig. 2.—Cross immunity test: Daily temperature records of (A) guinea pig inoculated with the known endemic typhus virus (Wilmington strain); (B) guinea pigs inoculated with the virus recovered from the sticktight fleas.

As indicated in Figs. 1 and 2, cross-immunity tests were found to be complete between the flea strain of virus and that of the known endemic typhus (Wilmington strain).

A rabbit was inoculated with testicular washings from guinea pig 97 infested with the flea strain of virus. The rabbit was tested at weekly intervals for the presence of *B. proteus* OX_{19} agglutinins in the serum, and the following results were obtained: Just before inoculation and one week later, no agglutination in any dilution; second week, complete agglutination (four plus) in the 1:10 and 1:20 dilutions and partial (two plus) in the 1:40 dilution. Third week, complete agglutination in 1:10, partial (two plus) in 1:20, and traces (one plus) in 1:40. Fourth week, complete agglutination (three plus) in 1:10 and traces (one plus) in 1:20.

The brain of one of the guinea pigs (No. 70) reported in these experiments was submitted to Dr. R. D. Lillie, of the National Institute of Health, Washington, D. C., for histological examination. Sections from this brain revealed lesions which in type and distribution were consistent with typhus infection.

SUMMARY

The virus of endemic typhus (Wilmington strain) has been successfully transferred to sticktight fleas as a result of allowing the fleas to feed on an experimentally infected

rat. An emulsion of the feces of these fleas and an emulsion of the body of these fleas produced clinical typhus when inoculated into guinea pigs.

Clear cut cross-immunity has been shown in guinea pigs inoculated with the virus from the fleas and with a known endemic typhus virus (Wilmington strain).

Histological examination of the brain of one of the guinea pigs inoculated with the strain of virus recovered from the fleas revealed characteristic lesions of typhus fever.

Agglutinins for *B. proteus* OX_{19} were demonstrated in the serum of a rabbit inoculated with the strain of virus recovered from the fleas.

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ZOOLOGY.—*Description of a new genus and species of copepod parasitic in a shipworm.* Charles Branch Wilson, State Teachers College, Westfield, Mass.[1] (Communicated by Waldo L. Schmitt.)

So far as known, the first internal copepod parasites reported from the shipworm, *Teredo*, are some that were discovered by Dr. C. H. Edmondson, of the University of Hawaii, in the course of a study of shipworms taken from Honolulu Harbor. In view of the large number of Teredos that have been handled in the course of many studies of these destructive mollusks, the copepod parasite here described can not be very common or it would have been found before. Concerning its occurrence, Dr. Edmondson has written me as follows:

"The copepod was first observed during the fall of 1939, when fully 75 percent of the specimens of *Teredo milleri* Dall, Bartsch, and Rehder, 1938 (B. P. Bishop Mus. Bull. 153: 209, 210) over 30 mm in length recovered from Honolulu Harbor were found to be parasitized. The parasite has appeared in shipworms at three additional localities about Oahu, and also in Hilo Harbor, Hawaii, and at Kahului, Maui.

"Six shipworms, five species of *Teredo* and one of *Bankia*, in Hawaiian waters are known to serve as hosts of the parasite.

"The female clings tightly to the lining of the infrabranchial cavity of the host by means of stout, sharp mouthparts, while the male is likely to be unattached in the cavity and when released from the host is capable of swimming quite freely. Because of the greatly inflated body the female is capable of but slight movement when detached from the shipworm."

Teredicola, new genus[2]

Diagnosis.—Female: First three thoracic segments enlarged and fused with the head into a cylindrical body. Fourth and fifth segments abruptly reduced in length and width; genital segment about as large as the fifth segment; abdomen 3-segmented; caudal rami slender rods, each tipped with two setae. Ovisacs as long as the enlarged anterior body; eggs minute and numerous.

Male: Much smaller than the female, first segment only fused with the head, the others free. The first four segments with lateral plates diminishing in size backward. Abdomen 4-segmented, segments about equal in size. First antennae 6-segmented; second antennae 2-segmented, prehensile; maxilliped one stout

[1] Dr. Wilson completed this paper some months before his death on August 18, 1941. Received October 28, 1941.

[2] Dr. Wilson did not specify the family for this genus, but in correspondence with Dr. Edmondson he mentioned that it "evidently belongs to the family Clausidiidae which includes many of the Cyclopoida that infest annelids and mollusks."—W.L.S.

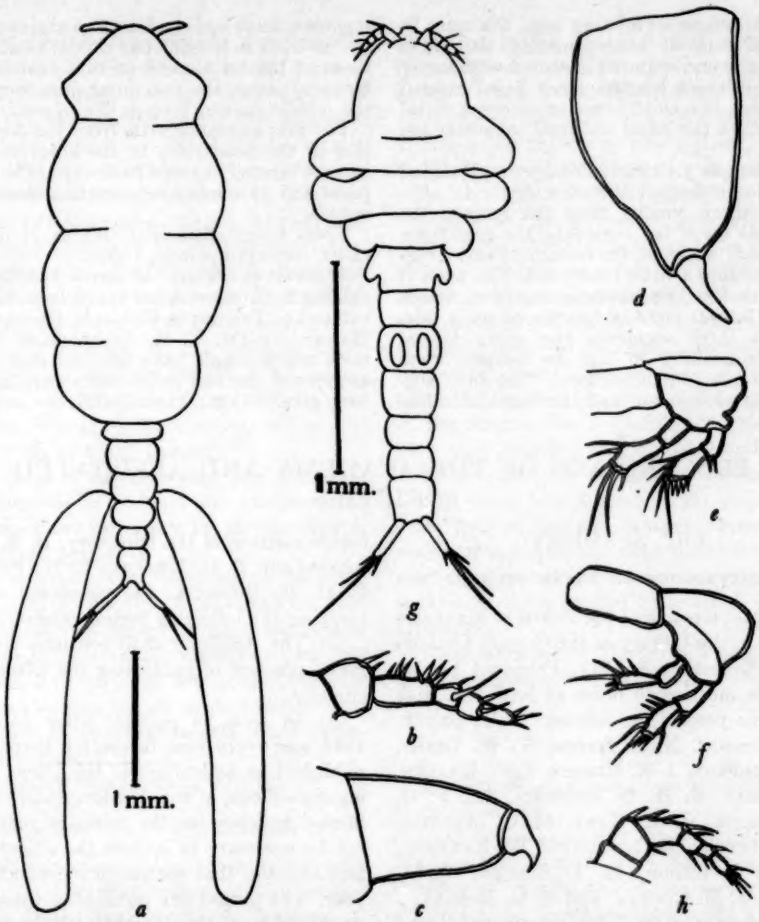

Fig. 1.—*Teredicola typica*, new species: *a*, Dorsal view of female; *b*, first antenna of female; *c*, second antenna of female; *d*, maxilliped of female; *e*, *f*, first and second legs of female; *g*, dorsal view of male; *h*, first antenna of male.

segment tipped with a claw. Two pairs of swimming legs biramose, rami equal and 2-segmented.

Genotype.—Teredicola typica.

Teredicola typica, new species

Fig. 1, *a-h*

Description.—Female: First three thoracic segments more or less fused with the head and with one another to form a cylindrical body a little more than twice as long as wide. Fourth and fifth segments reduced to a third of the width of the first and second segments, the fifth segment twice as long as the fourth. Genital segment about the same size as the fifth segment and subspherical in form. Abdomen 3-segmented, the first and third segments about the same width and length, the second segment shorter and a trifle narrower. Caudal rami narrow cylindrical, as long as the anal segment and widely divergent, each with two terminal setae as long as the ramus itself.

First antennae 6-segmented, the two basal segments considerably widened, the third segment the longest and the fifth segment the shortest, all except the basal segment bearing setae. The second maxilla and maxilliped are each made up of a single stout segment tipped with a strong claw, the one on the maxilla acute and curved into a semicircle, the one on the maxilliped blunt and nearly straight. Two

pairs of biramose swimming legs, the rami 2-segmented and of approximately the same length. Each end segment is armed with many setae of different lengths; each basal exopod segment has two small setae at its outer distal corner, while the basal endopod segments are unarmed.

Total length 4.43 mm. Enlarged cylindrical body 3.20 mm long, 1.50 mm wide.

Male: Much smaller than the female, the body made up of ten segments, the first three considerably widened, the remaining seven regularly tapering a little backward. The head is fused with the first thoracic segment, which carries a lateral plate or lamella on each side. The next three segments also carry lateral plates diminishing in size to become mere knobs on the fourth segment. The fifth segment, genital segment, and the four abdominal segments have convex lateral margins and differ but little in length. The caudal rami are like those of the female except that each has four terminal setae, the two outer ones very short, the middle ones as long as the ramus.

The first antennae arise from the dorsal surface of the head close to the anterior margin and are strongly curved backward. The mouthparts and swimming legs are like those of the female.

Total length 2.35 mm. Width of first segment, including wings, 1 mm.

Material examined.—A dozen specimens, including both sexes, were taken from the body cavities of Teredos in Honolulu Harbor, Oahu, Hawaii, by Dr. C. H. Edmondson. A single male and a female have been selected to serve as types of the new genus and species and have been given U.S.N.M. no. 79639.

PROCEEDINGS OF THE ACADEMY AND AFFILIATED SOCIETIES

THE ACADEMY

371ST MEETING OF THE BOARD OF MANAGERS

The 371st meeting of the Board of Managers was held in the Library of the Cosmos Club on Friday, December 5, 1941. President CLARK called the meeting to order at 8:07 P.M. with 19 persons present, as follows: A. H. CLARK, F. D. ROSSINI, N. R. SMITH, W. W. DIEHL, J. H. KEMPTON, J. H. HIBBEN, F. C. KRACEK, J. E. GRAF, F. H. H. ROBERTS, JR., F. G. BRICKWEDDE, R. M. HANN, M. C. MERRILL, W. A. DAYTON, H. L. CURTIS, W. RAMBERG, and, by invitation, R. J. SEEGER, G. A. COOPER, J. M. COOPER, and H. G. DORSEY.

The minutes of the 370th meeting were read and approved.

President CLARK announced the following appointments: Committee of Tellers, L. B. TUCKERMAN (chairman), R. W. BROWN, and GEORGE TUNELL; Committee of Auditors, P. A. SMITH (chairman), H. G. AVERS, and C. H. SWICK.

Chairman GARNER of the Committee on Meetings reported that the December meeting of the Academy would be held in the Auditorium of the U. S. National Museum.

The Board considered individually and duly elected to membership the seven persons (six resident and one nonresident) whose nominations had been presented on November 7, 1941.

The Committee to consider the policy for future editions of the Directory, H. L. CURTIS (chairman), F. C. KRACEK, L. W. PARR, and F. H. H. ROBERTS, JR., presented a report carrying the following recommendations:

(*a*) The Academy shall continue the established practice of publishing the Directory biennially.

(*b*) As soon as possible after January 1, 1942, and every year thereafter, there shall be published an addendum to the Directory, giving the officers of the Academy and of the affiliated societies for the calendar year. It will not be necessary to include the officers of certain societies that change in the middle of the year. The format for publishing these addenda should be at the discretion of the Secretary and Treasurer.

(*c*) In future editions of the Directory, there shall be reserved space for the officers of the two following years. This space, for each society, shall come directly under the list of officers and shall have printed across it "Reserved for officers for 1944, etc."

(*d*) The publication of the Directory shall be entrusted to the Secretary and Treasurer.

The Board approved this report, with the insertion of "and new members of the Academy" at the end of the first sentence in part (*b*). It was further moved and carried that these addenda be supplied to all members of the Academy and to all purchasers of the Directory.

The committees on awards for scientific achievement for 1941, J. M. COOPER, General Chairman, reported that the work was completed. For the committee on the biological sciences, Chairman J. M. COOPER recommended that the award for 1941 be presented to G. ARTHUR COOPER, of the U. S. National Museum. For the committee on the engineering sciences, Chairman H. G. DORSEY recommended that the award for 1941 be presented to THEODORE R. GILLILAND, of the National Bureau of Standards. For the committee on the physical sciences, W. E. DEMING, chairman, President CLARK reported a recommendation that the award for 1941 be presented to STERLING B. HENDRICKS, of the U. S. Bureau of Plant Industry.

On request of the Secretary, the Treasurer was authorized to increase the allotment for the office of the Secretary by the amount of $49.85 for the year 1941.

The Custodian and Subscription Manager of Publications, W. W. DIEHL, reported that the situation with regard to back volumes of the JOURNAL was vastly improved and that there were now on hand seven complete sets and one set lacking but six single numbers, and that to date three complete sets of the JOURNAL have been sold.

Adjournment was made at 9:07 P.M.

308TH MEETING OF THE ACADEMY

The 308th meeting of the Academy was held jointly with the Washington Section of the American Institute of Electrical Engineers in the Auditorium of the U. S. National Museum at 8:15 P.M. on Thursday, December 18, 1941, with H. L. CURTIS, Vice President of the Academy, representing the Washington Section of the American Institute of Electrical Engineers, presiding. KARL B. MCEACHRON, research engineer in charge of the High Voltage Engineering Laboratory of the General Electric Company at Pittsfield, Mass., delivered an illustrated address entitled *Lightning*. DR. MCEACHRON told the story of researches on lightning and described the production of lightning artificially, the photographing of natural lightning, the effects of lightning discharges as a function of location and their relation to old superstitions and beliefs, and the investigation of a number of so-called "pranks" of lightning. He disclosed that deaths from lightning have averaged 390 annually for this country since 1924, just a little more than attacks from animals and only a tiny fraction of the deaths caused by automobiles; that the real danger of lightning is to property; that office buildings and factory buildings offer excellent protection to their occupants; that suburban homes are not so likely to be struck as isolated buildings on a farm; that the ordinary lightning flash seen by the observer is not a brilliant bolt from the sky, but rather the union of a cloud streamer with another streamer from the earth; that lightning may strike many times in the same place, as it has on the top of the Empire State Building in New York City; that lightning rods do not keep lightning away but serve to attract the electrical discharge and to lead it safely to the ground; that every flash of lightning is not accompanied by a clap of thunder; and that thunder is the result of a pressure wave caused by the sudden expansion of air created by a quick lightning discharge.

There were about 175 persons present. The meeting adjourned at 10:15 P.M.

NEW MEMBERS

The following persons were recently elected to membership:

ERNEST GOLSAN HOLT, chief of the Wildlife Management Section, U. S. Soil Conservation Service, in recognition of his biological and ornithological investigations and, more recently, his contributions to wildlife management.

HERBERT LUDWIG JACOB HALLER, principal chemist, Division of Insecticide Investigations, U. S. Bureau of Entomology and Plant Quarantine, in recognition of his contributions in the field of insecticidal chemistry, particularly with regard to pyrethrum flowers.

MILTON HARRIS, director of the Textile Foundation Research Associateship at the National Bureau of Standards, in recognition of his work on the chemical and physical structure of the textile fibers, wool, silk, cotton, and rayon.

MARIO MOLLARI, professor and director of the Department of Bacteriology and Preventive Medicine, Georgetown University, in

recognition of his work on the diseases of man caused by fungi and bacteria.

JACINTO STEINHARDT, physical chemist on the Textile Foundation Research Associateship at the National Bureau of Standards, in recognition of his studies on the chemical structure of the wool molecule.

FREDERICK LOVEJOY WELLMAN, associate pathologist, U. S. Bureau of Plant Industry, in recognition of his contributions in plant pathology and in particular his researches on club root of crucifers, banana wilt, and tomato wilt.

HALBERT MARION HARRIS, associate professor of entomology, Iowa State College, Ames, Iowa, in recognition of his work in the field of systematic entomology, in particular in the classification of the Hemiptera.

JOSEF PIKL, research chemist, E. I. DuPont de Nemours & Co., Wilmington, Del., in recognition of his contributions to the chemistry of the compounds of the indol series.

HERBERT HOLDSWORTH ROSS, systematic entomologist, Illinois State Natural History Survey, Department of Education, Urbana, Ill., in recognition of his work in insect taxonomy, with special reference to the classification of the sawflies and caddisflies.

HARRY AARON BRIGHT, chief of the Section on Metal and Ore Analysis and Standard Samples, National Bureau of Standards, in recognition of his work in metallurgical analysis.

REGINA FLANNERY, research associate, Department of Anthropology, Catholic University of America, in recognition of her contributions to the anthropology of the Algonquian peoples, especially the northeastern and eastern.

WILLIAM MCKINLEY GAFAFER, senior statistician, National Institute of Health, in recognition of his statistical investigations in the field of public health, and his studies in medical history.

GUSTAV ERNST FREDERICK LUNDELL, chief of the Division of Chemistry, National Bureau of Standards, in recognition of his work in inorganic analytical chemistry.

PAUL SALMON ROLLER, physical chemist, Eastern Experiment Station, U. S. Bureau of Mines, in recognition of his contributions to the physical chemistry of nonmetallic minerals, especially with reference to the properties of fine particulate matter and the measurement of these properties.

LEWIS WILLIAM BUTZ, biochemist, U. S. Bureau of Animal Industry, in recognition of his work in organic chemistry and biochemistry, and in particular that on diene syntheses of condensed ring systems related to the steroids.

JOHN PUTNAM MARBLE, research associate in geochemistry, National Research Council, in recognition of his contributions to mineral analysis, with particular reference to the estimation of geologic time.

JOHN R. MATCHETT, chemist, U. S. Bureau of Narcotics, in recognition of his work in the chemistry of narcotic drugs, particularly cannabis (marihuana).

WILLIAM HENRY SEBRELL, chief of the Division of Chemotherapy, National Institute of Health, in recognition of his contributions to the study of human and animal nutrition, in particular on pellagra ariboflavinosis.

JAROMIL VACLAV SLADEK, instructor in biochemistry, Georgetown University, in recognition of his work in biochemistry and organic chemistry.

JOHN TUCKER, JR., Chief of the Section on Cement and Concrete, National Bureau of Standards, in recognition of his studies in concrete and in the application of the mathematical theory of probability to problems in the strength of materials.

LEON WILSON HARTMAN, president of the University of Nevada, Reno, Nev., in recognition of his contributions to radiometry and electrical measurements.

FREDERICK D. ROSSINI, *Secretary*

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